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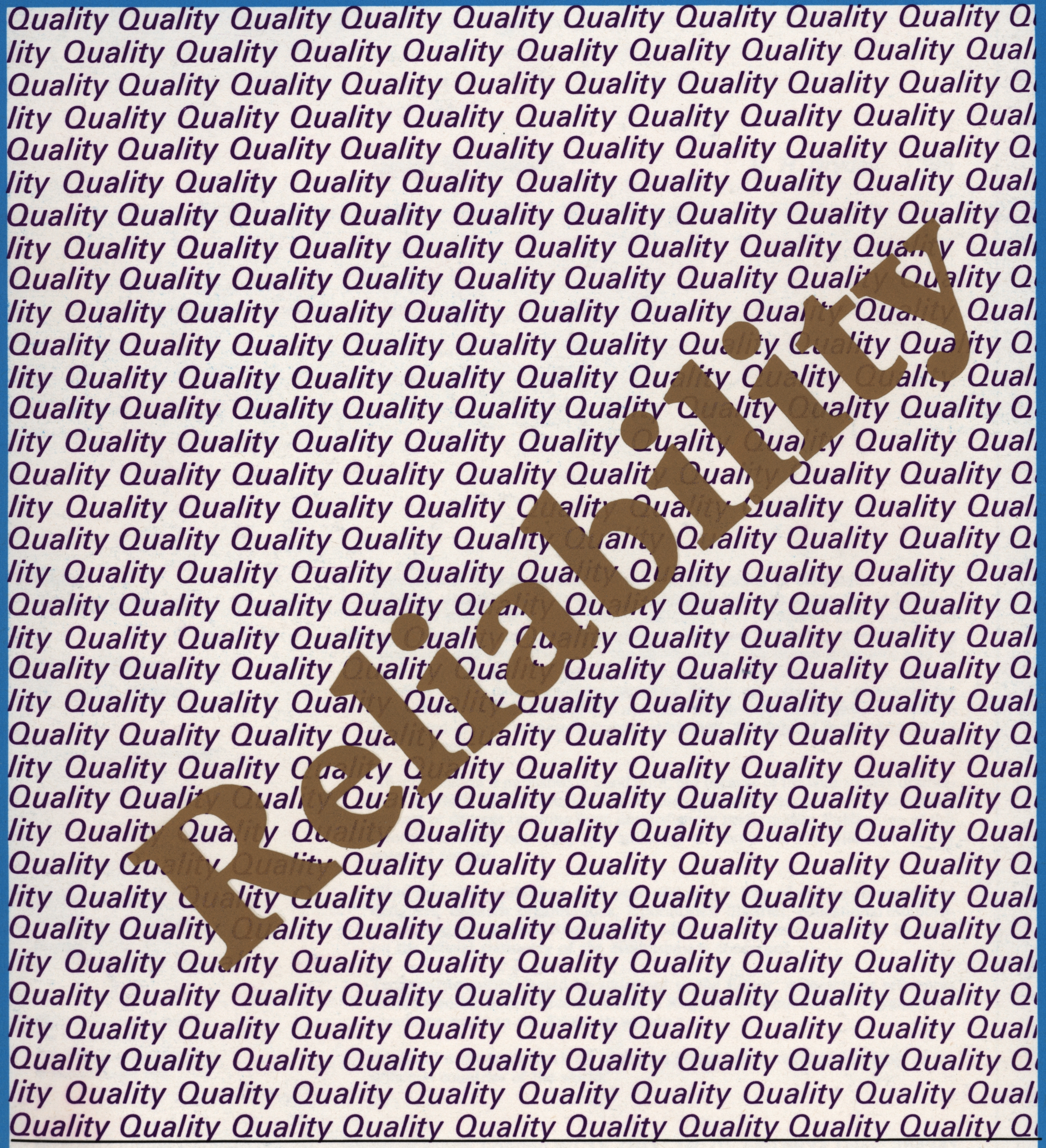
Quality
Reliability

- Design for reliabilty

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This journal records developments in the application of electronics in science, industry, and the home. It contains information on the properties and performance of solid-state devices, valves and tubes, and associated components and assemblies. The practical circuits given are designed to provide the best working conditions and performance for the devices used. The design principles may be used (so far as device ratings allow) for adaptation to meet particular requirements. Current data should be consulted before any circuit is considered for production. Mullard Limited can normally supply only those devices or assemblies listed in the Company's current catalogues. Availability in quantity should be confirmed.

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Four issues are published each year and issued free of charge to equipment designers, research organisations, laboratories, libraries, educational establishments, and consultants. Requests for addition to the mailing list must be made on the official stationery of the establishment concerned.

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Editorial

'Mullard Technical Communications', known to many as 'MTC', has now reached the mature age of twenty-four years, and we hope to continue well past the quarter-century. Our continuing aim is to fulfil the original objective of giving wide circulation to the application information which is created in our laboratories. We stated clearly in the first issue in May 1952 that we wanted to provide assistance in using our electronic products: this has been achieved consistently down the years by selecting laboratory reports which are likely to have an adequately large readership, editing these and often extending them, and printing them in this journal for a worldwide readership greater than ten thousand. This general procedure is still followed. We have adapted, however, to all the new technologies in electronics; we have also, incidentally, modernised the production and presentation of MTC particularly with the new cover design.

The journal draws nowadays on an even wider network of laboratories and factories for up-to-date information. We have an increased number of specialist engineers and scientists to consult. We have a highly qualified and experienced editorial team to bring articles to the high standard of intelligibility, presentability, and completeness which the readership has come, quite rightly, to expect. We also take steps nowadays to ensure that readers are made aware of recently-introduced electronic components, where these have a major significance, even before detailed application information becomes available.

The present issue terminates the thirteenth volume of MTC with an article that embraces all our products and all the application areas. 'Design for reliability', presented by one of the MTC editorial team, gives background information on the high quality of our products, and also gives extensive information on how the circuit designer can achieve maximum reliability in his equipment with our components.

Mullard will go on producing high-quality components. Our laboratories will go on producing vital application information. MTC will continue to keep the reader in contact with Mullard thinking. This is a combined effort to help sustain a healthy electronics industry and we are proud to be associated with the industry in this way. We look forward to making further regular contributions to its advancement through this journal.

The Editor

Design for reliability

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In designing high-reliability electronic equipment, it is necessary to make an appropriate choice of components, and to ensure that their embodiment and the design of the circuit are both conducive to reliable operation.

INTRODUCTION

A primary attribute of any equipment is its ability to provide the required service under any of a range of circumstances for a period of time: loosely, its reliability*. The reliability of an equipment might be expected to be inversely proportional to its complexity, but this is not generally the case for equipment in large-scale production. A piece of equipment must reach a certain standard of reliability to gain acceptance. Hence, with increasing complexity of equipment, the reliability of individual components must be correspondingly increased.

In the field of electronics, new systems and new technologies are introduced before the engineering practices for assuring their reliability have been fully developed. In such cases the contribution of electronic components to system reliability is more difficult to predict, and where high reliability is required the designer can do no more than use his best judgment in selecting components of assured quality and operating them under conservative conditions.

The rapid growth of television in the late 'forties and 'fifties, and the smooth conversion to colour television, are eloquent tributes to the industry. Proven reliability of existing equipment is a prerequisite of further growth of electronics.

Reliability, which is a measure of quality, is an essential element at each stage of the equipment manufacturing procedure – from the initial specification of the equipment, through design and production, to final delivery to the user. Furthermore while each of us has a clear notion of the meaning of reliability, its implementation is intimately concerned with the product under discussion. For these reasons this article cannot be consistently specific, but must deal with a collection of items of general interest which, given the attention of the designer, can contribute to the achievement of equipment reliability.

In designing a piece of equipment for improved reliability, the factors to be considered are manifold and interacting. For simplicity, in this article an attempt is made to divide them into three groups.

1) *Component reliability* The selection of appropriate component types is essential in equipment which is designed for reliability. Furthermore, as the reliability of a component is reduced by operating it at ratings above those recommended, so (in many cases) can the reliability be increased by operation well below the recommended ratings.

2) *Environmental effects on reliability* Components must be provided with suitable layout, adequate heat-sinking, and protection against voltage transients and surges. The physical handling of the equipment and the special requirements of automobile and aircraft equipment must be borne in mind, as well as the ambient conditions under which the equipment is to operate.

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*For a more rigorous definition of reliability, see Appendix 1.

3) *The effect of circuit design on reliability* The circuit must be designed with a view to the compatibility of the various component tolerances, at all extremes of operation, and to the possible effects on other components of a single component failure. The function of every component must be related to its capabilities as embodied in the published data.

The present article draws many of its examples from colour television design practice, and makes no apology for this. Television sets are the most widespread type of electronic equipment; they use a wide variety of components and circuit techniques; they are 'operated' by unskilled 'personnel' and therefore must resist many different types of stress; the operating ambient conditions are uncontrolled; and the competitive market demands high reliability at low cost.

RELIABILITY AND EQUIPMENT DESIGN

Detailed consideration of total equipment design is a long, laborious, unglamorous task calling for great discipline. A good design is a combination of science and art, past experience and careful examination of available information. Codes of good practice have been established over the years; component manufacturers provide comprehensive information in published data, often supported by applications information. For more critical applications, derating information is provided and safe operating areas (SOARs) are defined.

The designer's task is:

1) to define clearly the intended function of the equipment and the acceptable limits of performance;
2) to assess the effects of component tolerances;
3) to specify the range of operational conditions and their effect on the design;
4) to examine the likely environmental conditions: temperature, humidity, vibration, mains pollution, etc.;
5) to determine the effects of component interaction within the complete equipment;
6) to establish the overall equipment layout;
7) to ensure compliance with relevant national and international regulations;
8) to design the equipment taking appropriate note of the above considerations.

Other requirements, such as costing, ensuring ease of manufacture, and establishing test procedures, may also fall within the designer's province.

Published data

Mullard published data constitute a primary source of design information, stating the intended purpose of each component, and the design operating conditions and limiting values. They give the tolerances of the major component parameters, and SOAR and applications information. Where appropriate they provide information on mounting, handling, and soldering, and they indicate any incidental hazards associated with the operation of the component.

Published data reflect the characteristics of the total population of a component type, and stated limits of parameters are therefore wider than those which would be found by measurements on a random sample. Extra effort may be required from the designer to handle this wide tolerance, and it is tempting to base the equipment design on the measured results obtained from the sample in hand rather than on those published in the data. This is bad practice: in the course of a few months the component characteristics may change slightly – remaining within the limits published – leading to equipment failure or reducing the equipment reliability.

Applications information provided in the data is based on assessment of many parameters and extensive life-tests. Because of the limited space available it is impossible to state all the factors considered for justification in detail of the recommendations. A result may be, for example, that the data recommends a large heatsink, while laboratory measurements on a number of samples indicate that the component dissipates only moderate power. In such cases it is worthwhile to follow the recommendations of the manufacturer.

It is a statistical truism that a component whose parameters have average values can easily be selected from the total population, whereas it is difficult to select a component having a parameter near its limit. To select a device with several parameters at their limits, particularly if some of the limits are reached only at elevated temperatures, is a daunting task: if it is evident that for satisfactory equipment performance such an extreme selection is necessary, then advice should be sought from the component manufacturer.

The limits and applications recommendations in the published data are derived to provide satisfactory equipment life. The life may be extended by additional component derating: this subject will be examined in more detail later. Nevertheless, not every component of an equipment should be derated. While it is reasonable to reduce, for example, the peak collector voltage or current of a tv line output transistor, it is essential to provide adequate drive. Again, a reduction in picture tube heater voltage will give shorter life and poor performance.

In general, published data do not provide any classification of the limiting values given, whereas it is common knowledge that, for example, an excessive voltage on a transistor will cause a catastrophic failure while an excess of the same proportion on the focus electrode of a picture tube will do no harm. The explanation is that the data are compiled to ensure safe operation, long life, and uniformity of products. It is essential to bear in mind that in some cases even a momentary excess can lead to catastrophic failure. Care must then be exercised with the addition of tolerances: most of them may have to be added arithmetically instead of statistically.

COMPONENT RELIABILITY

Mullard continuously assesses the quality and reliability of its products, by analysis of the results of tests carried out during and after manufacture. In the short term, these results are used to define the quality of production, and to highlight areas where the process could be improved. Information obtained over a longer period, especially from life tests under varying conditions, makes it possible to offer the customer a product of proven and well-defined reliability (and in some cases to offer a range of functionally similar components having varying reliability, with appropriate price differentials).

In many cases it is technically feasible to produce components which are virtually infinitely reliable. The price of such components and of equipment constructed from them would, however, be prohibitive unless (as is the case with certain defence and aerospace equipment) failure of the equipment cannot be tolerated under any circumstances.

Nevertheless, equipment manufacturers are willing to pay the moderate cost of a moderate improvement in reliability, because they must consider not only the initial component cost but also the total cost of their product over its useful life-span. (The equipment consumer, choosing between a number of alternative products, must solve a similar problem with, usually, much less authoritative guidance.) The variables of the 'total reliability cost' of an equipment comprise the initial cost of the components and the cost of field service. Reliability information from the component manufacturer, as well as from his own service department, can enable the equipment manufacturer to trade off increased component cost against either decreased service and warranty costs, or a longer warranty period and the improved image and increased sales of his product.

Generally, though not invariably, the reliability of a component improves when it is operated further within its ratings; that is, when less stress is placed upon it. The kinds of stress to which a component is subjected are indicated by its ratings: they include peak and continuous voltages and currents, ambient and junction temperatures, duty cycle, etc., but normally the effect of any form of stress is to increase the temperature of the component, and this accelerates the various physical and chemical mechanisms which lead to failure.

To improve the reliability of an equipment, therefore, it is possible to select components more generously rated so that operation well within the ratings is achieved. The component used is said to be *derated*, and the excess of its cost over that of a component which would perform the same function but at the limits of its ratings constitutes the reliability trade-off. The degree of derating applied to components in an equipment can be determined by the length of the equipment useful life, if the cost of the service that would have been necessary is balanced against the increased cost of the derated components.

Derating to improve reliability

It is easy to accept the idea that using an article under lenient conditions is likely to be advantageous. The advantages that can be realised include the following.

1) The useful life of normal, well-made products may be lengthened.
2) The probability of failure of products which are nominally good but which contain unusual weaknesses (because of manufacturing abnormalities, for example) may be reduced.
3) Where the conditions of use are not fully controlled, the product may be better able to withstand unexpected or unknown stresses, which would otherwise be damaging or destructive.
4) The stability of the product characteristics may be increased.
5) The expense of time and money, which would in some cases be necessary for exact determination of component operating conditions, may be avoided.

The operation of products under reduced-stress conditions, with the object of achieving any or all of the above advantages, is termed derating. The practice of derating is widespread in many industries, although it is not always called by that name. In all cases the ultimate object of derating is either to improve the reliability of the product (that is, to extend its useful life or to reduce the rate at which products fail), or to avoid the necessity of making a detailed study of the conditions of use. In this section of the article, the application of derating techniques to discrete semiconductor devices is considered; the principles discussed may be applied to integrated circuits and to other components but the corresponding elements in these other products may necessitate considerable difference in the application of the principles.

Ratings of electronic components

A rating is a declaration or statement about the stresses that a product may be expected to withstand, or the performance that it should give, or its capabilities in use. If a rated parameter is exceeded then the component may be expected to fail: either immediately, or in an unacceptably short time.

Because of the different failure mechanisms of different component types, and also for historical reasons, several rating concepts have been found necessary. Within the IEC, for example, three rating systems are used: the absolute maximum, design-centre, and design-maximum systems. These are defined and explained in Appendix 2.

For Mullard semiconductor devices, the absolute maximum rating system is usually applied, primarily because most semiconductor failure mechanisms are due to absolute stress levels which when exceeded cause failure, almost independently of the duration of the excess. There are, however, a number of failure mechanisms in which time is a factor, and therefore in these cases a reduction in the stress reduces the rate of activity of the failure mechanisms.

For many electrical and mechanical products, the predominant failure mechanisms are time-dependent, and there is in most cases a direct relationship between length of life, or failure rate, and stress level. It is particularly important that these conceptual differences are understood for semiconductor devices, because two different rating philosophies may converge in one equipment.

For example, a semiconductor device whose ratings are based on the absolute maximum system may form part of a power drive system, directly or indirectly controlling an electric motor which is rated according to a mean rating system. In this situation two industries, each with its own traditions and established 'good practice', come into contact, and it is necessary carefully to consider the compatibility of the individual 'good practices'. Some semiconductor devices are sensitive to transient voltage overloads, and so good practice includes ensuring that they do not occur. By comparison, electric motors are less susceptible to damage due to transient overvoltages of short duration. Thus certain design considerations that can be ignored in one area may require very careful study in another. When two types of product meet in a common environment, one solution is to avoid operating near the maximum rating of the electronic component. In this way the necessity of closely studying the precise operating and environmental conditions is avoided.

How ratings are determined

The design of a new component to meet the target electrical and mechanical ratings represents a compromise taking account of many factors, including:

performance;
length of life;
freedom from chance failure;
immunity to misuse;
scale of manufacture;
adaptability to current production methods;
cost.

For semiconductor devices the principal electrical parameters are those of voltage, current, and power; the principal environmental and mechanical stresses are temperature and humidity. Each of these quantities is given a rated value according to the absolute maximum system; it is not permissible, however, for all the parameters to be stressed to their maximum ratings simultaneously. Thus there is a set of relationships between the maximum value of any one parameter and those of the other parameters: a matrix of limiting values, which is the boundary of the various combinations of parameter limits within which the component can be expected to perform satisfactorily.

To obtain a rating for a newly-designed electronic component, the starting point must be the properties of the materials used in the component: the melting points and fusing currents of internal wire connections, for example. It is then necessary to consider limiting factors due to component operation, such as the gain reduction with increased current in transistors, and voltage breakdown in capacitors. The effect of the component on the environment in which it is used provides further limitations: a resistor intended for printed-wiring board mounting must be rated so that the board is not damaged. Finally, the component application is considered. If a transistor is intended for application in a television tuner where it will operate at 12V and from 2 to 12mA, then it need not be rated for more than 20V and 20mA.

Example: Rating a power transistor

Now let us consider the detailed steps in defining the ratings of a power transistor. For this purpose the device will be treated as a black box with no closely specified application. The voltage rating in the first instance would be controlled by the breakdown voltages of the junctions: the collector-emitter breakdown voltages $V_{(BR)CEO}$ are shown in Fig.1. The shaded area shows the spread of characteristic given by the production method. Voltage V_1 is the lower limit of the spread, and so if all the product is to be used then the V_{CEO} rating cannot exceed this figure. Mullard would usually place the lowest voltage rating of a product below the actual spread of the voltage seen. When a higher rating is demanded from this product, then a selection would be made as shown by V_3. The collector-base and emitter-base voltage ratings would be defined in a similar way.

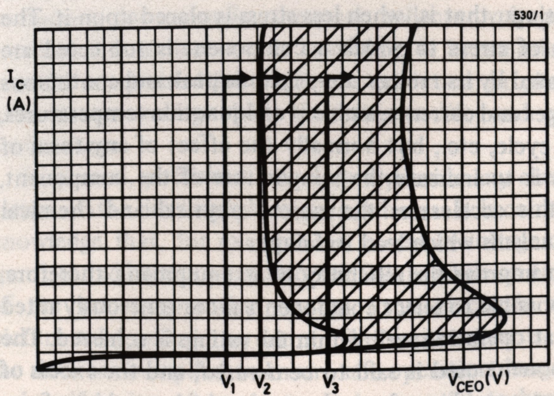

Fig.1 – Spread of collector breakdown characteristics (typical)

The current rating of a transistor is in the first place controlled by the amount of current the bond wires can withstand, and so the first test would be to carry out fusing tests on the emitter and base bond wires.

Fig.2 shows the forward current gain h_{FE} plotted against collector current I_C for two practical cases (A) and (B) that may be met during current rating tests. The rating line XX can be considered for both cases. For transistor A it is a safe level of I_C, well below the fusing current. For transistor B the gain is no longer usable, and so there is no real point in extending the rating. This defines the collector current. The base current would be defined by that which is required for useful operation of the transistor. Some power transistors which operate with gains as low as 4 could have a base current rating equal to half the collector rating.

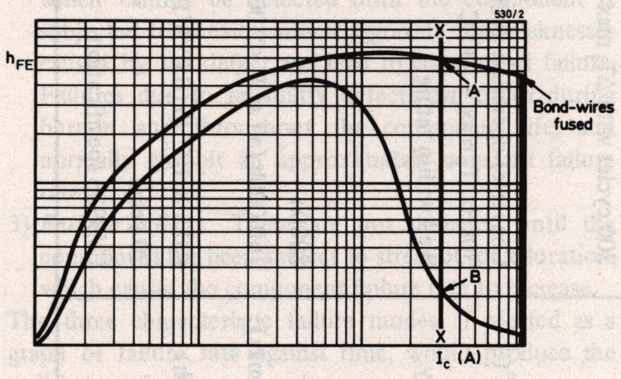

Fig.2 – Variation of current gain with collector current for two practical cases

The temperature rating will be defined by carrying out reliability tests for high- and low-temperature storage, and for thermal cycling (power cycling and rapid change of temperature). These would be supplemented by tests to determine thermal runaway points for the leakage current, and the effect of keeping the device at high temperature with the rated voltages applied to the junction (cut-off tests). The results of these tests will give the lowest and highest temperatures at which the device can be safely used and also the amount of cycling the structure can withstand, as shown in Fig.3.

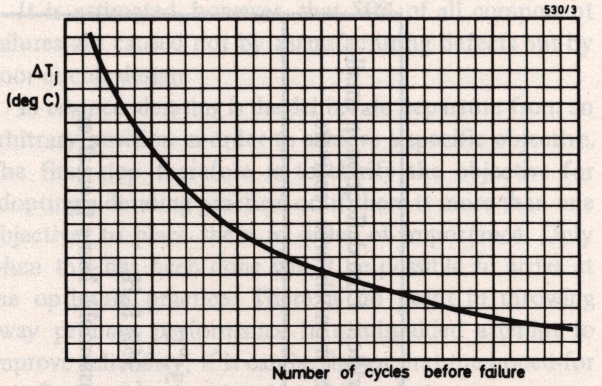

Fig.3 – Magnitude of temperature variation plotted against number of cycles to failure (schematic only)

We have now determined three discrete ratings, but we do not know how they can be combined. It is normal for the voltage and current ratings to apply up to the rated temperature, but the combination of voltage and current is strongly dependent on the thermal characteristics of the transistor.

The modern way of defining the power permitted is to produce a Safe Operating Area (SOAR) curve (Fig.4), and this procedure has been fully described in Ref.1. The technique can be summarised by Eq.1 which is applicable provided the crystal maintains good current distribution:

$$V_{CE} \times I_C = \frac{T_j - T_{amb}}{R_{th(j\text{-}amb)}} \quad . \qquad \ldots (1)$$

For transistors which exhibit second breakdown (Ref.1), the permissible current at higher voltages is reduced. The reduction in the SOAR is shown in Fig.4, by the boundary line B.

Although the results of endurance tests were used in determining the temperature rating, we have yet to combine current, voltage, and temperature, and to assess the failure rate, useful life, and stability of characteristics when using the complete ratings. Mullard does this against a target of the specific application requirements or a general-purpose reliability specification. Only when acceptable results have been achieved is a product released to the market. Table 1 gives, as an example, a reliability specification for a power transistor.

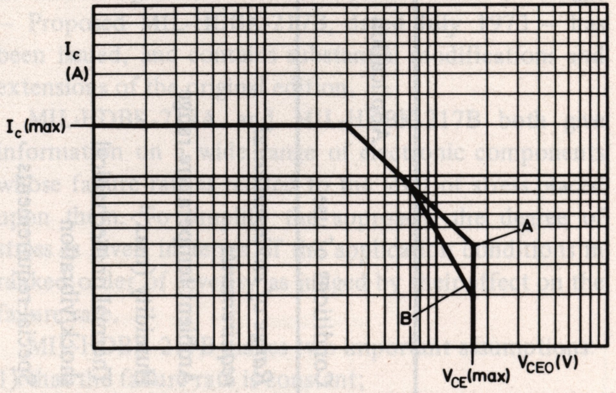

Fig.4 – Safe operating areas for two power transistors

TABLE 1

Proposed M424BD (BUY86) Reliability Target Requirements

Conditions of use	Application: Lighting inverter application: Mobile (bus, aircraft, etc.)	Application: Post Office switched-mode power supply (TXE4 Central Exchange)	Application: Television: Line deflection in small-screen monochrome receivers
Range of environmental requirements			
Ambient temperature range	−20 to 50°C	0 to 35°C	0 to 35°C
Humidity (max)	35°C 95% R.H.	35°C 95% R.H.	35°C 95% R.H.
Thermal or mechanical shock/vibration	Applicable to mobile application	BS 9000 requirements	TV assembly. None thereafter
Special requirements	Nil	As BS 9000	Nil
Electrical stress requirements			
Power cycling (in useful life)	6000 cycles with ΔT_j max = 100°C (1500 cycles approx. between −20 and 100°C)	200 cycles with ΔT_j max = 75°C	10 000 cycles with ΔT_j max = 100°C (500 cycles with ΔT_j max = 115°C during out-of-sync conditions)
A.C. operation	As in inverter (T_j max = 150°C)	Converter operation at 20 to 30kHz, T_j max = 100°C	Line timebase
Transient operation (pulse power, or voltage or current transients)	Switching transient on supply, but within rating	Well within rating	Tube flashover, mismatch, and out-of-sync conditions
Reliability requirements			
Use time/year	1500h	8000h	2000h
Useful life	15 000h (approx. 50% at T_j max)	160 000h (all at T_j <100°C)	20 000h (approx. 19 000h at T_j = 125°C, 1000h at T_j = 150°C)
Complete failure rate	$<16.6 \times 10^{-6}$/h (1.6%/1000h)	$<0.5 \times 10^{-6}$/h (0.05%/1000h)	$<3.5 \times 10^{-6}$/h (0.35%/1000h)
Existence time	10 years	20 years	10 years
Mandatory assessment requirements	Nil	CV9936 specification	Possible BS 'TV' specification

From the foregoing discussion it will be seen that while the SOAR curves set the boundary limits, they give only a rough indication of the quantitative advantages, from the reliability viewpoint, of operating within the SOAR.

What derating can achieve

Defects in electronic components can be divided into three groups, which can be distinguished broadly by the time at which they occur.

1) *Quality defects* These can be detected at any time after manufacture. Defects of this type are not normally a serious problem: they can be identified at final inspection, during commissioning of the equipment, or during a short burn-in period. It is estimated that 95% of quality defects will be identified at these times.
2) *Reliability defects* This term is applied to defects which cannot be detected until the component is subjected to stresses, which aggravate the weaknesses caused by the defect and lead to component failure. Failures due to reliability defects can occur during burn-in and throughout the component life, and normally exhibit an approximately constant failure rate.
3) *Fatigue defects* These are not detected until the component has been subject to stress of long duration, which causes the component failure rate to increase.

The three characteristic failure modes, if plotted as a graph of failure rate against time, would produce the well-known 'bath-tub curve'.

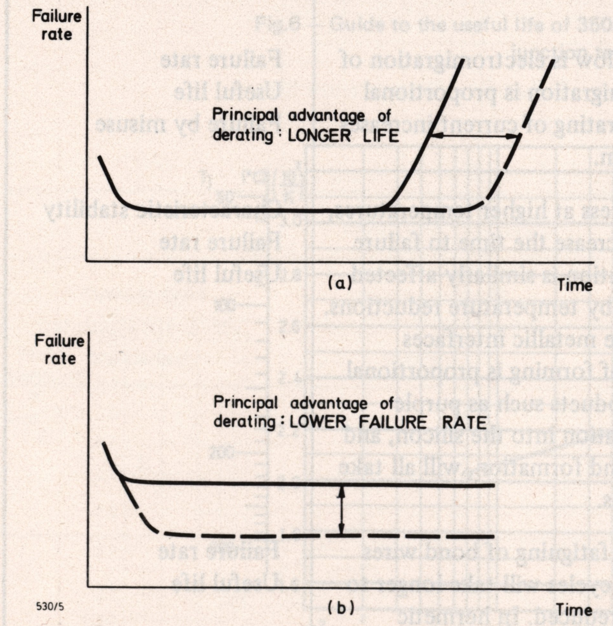

Fig.5 – Indication of the effects of derating on:
(a) a product with a predominant wearout mechanism
(b) a product without a predominant wearout mechanism

It is estimated, however, that 50% of all component failures are caused not by manufacturing defects but by poor circuit design.

In essence, derating is the deliberate departure from an arbitrary position in order to achieve a specific objective. The first step therefore is to clarify the objective for adopting a derating practice, or, if there is more than one objective, to place them in order of importance. Only when this has been done will it be possible to arrive at the optimum practice. There is no point in throwing away product performance in a misguided attempt to improve reliability, if it can be shown that the hoped-for benefits have no sound technical foundation.

The need to distinguish between objectives may be illustrated by considering again the two cases mentioned earlier: a discrete semiconductor device and an electric motor. The semiconductor device may be derated by operating at a voltage or temperature – or both – well below the maximum rated values. The advantage would be realised as a reduction in the failure rate; that is, the nominally constant rate at which random failures occur. In the case of the motor, derating may be effected by reducing the torque load. The advantage of this would be an increase in the useful life of the motor. These contrasting cases are illustrated by Fig.5.

Some semiconductor devices contain long-term wearout mechanisms, and in these cases derating may affect the useful life, as well as the failure rate. For most semiconductor devices, however, the wearout point need not be taken into account when considering derating, and recognition of this concept is implicit in the well-known failure rate handbook MIL-HDBK-217A (Ref.2). This document, issued in December 1965, was based on the experience of using MIL-approved components in military equipment in the U.S.A. There appears to be no other document of comparable scope, and MIL-HDBK-217A has been widely used for this reason alone.

Recent experience, however, has shown that the figures indicated are often invalid for components of other types and from other sources, even though they may fall in the same category as those in MIL-HDBK-217A. It is significant that a new edition of the document – Proposed MIL-HDBK-217B, dated July 1973 – has been issued, and contains substantial modifications and extensions of the original edition.

MIL-HDBK-217A and MIL-HDBK-217B both give information on a wide range of electronic components whose failure rate is related to the level of stress placed upon them. To simplify the approach, the degree of stress is given in terms of the application conditions in ranked order of severity as judged by their effect on the failure rate.

MIL-HDBK-217B makes two important assumptions:

1) that the failure rate is constant;

2) that the duration for which the failure rate is constant is greater than the required length of component life (although no indication is given of what this may be).

At the time of writing, MIL-HDBK-217B has not received approval and may not be used for U.S. Government procurement purposes. Furthermore, as is the case with MIL-HDBK-217A, it cannot be assumed that the data are valid for components of other types and from other sources.

Transistors

It is useful to reflect on the failure mechanisms which can be affected by derating, to obtain a better understanding of the foundations of derating technique. Table 2 presents the relation between the media of derating, their effects, and their objectives. Because of the variety of failure mechanisms which are affected to varying degrees, the choice of a particular medium of derating may not have a uniform effect on all the objectives. Furthermore, because different versions of nominally similar devices may utilise different methods of construction, and therefore contain different failure mechanisms, the different versions may vary in their response to the same medium and amount of derating.

TABLE 2

Media and Objectives of Derating Semiconductor Devices

Medium of derating	Physical effect	Derating objective
Voltage	Reducing the working voltage applied to a transistor slows down the rate of deterioration of the surface, which shows itself by characteristic drift of leakage current and current gain (h_{FE}).	Characteristic stability
Current	The main defect caused by current flow is electromigration of metallisation patterns. The rate of migration is proportional to the current density. Therefore derating of current increases the time to failure by this mechanism.	Failure rate Useful life Failure by misuse
Temperature	Surface deterioration is a faster process at higher temperatures, therefore temperature reductions increase the time to failure due to this mechanism. Electromigration is similarly affected by temperature and is slowed down by temperature reductions. Intermetallic compounds form at the metallic interfaces throughout the structure. The rate of forming is proportional to temperature, therefore failure products such as purple plague, diffusion of the top metallisation into the silicon, and back contact failure due to compound formation, will all take longer to form at lower temperatures.	Characteristic stability Failure rate Useful life
Temperature swing	In plastic transistors the mechanical fatiguing of bond wires due to temperature cycles or power cycles will take longer to develop if the temperature swing is reduced. In hermetic transistors the failure of back contacts, due to mismatch of expansion coefficients between the silicon material and the header material, will be similarly proportional to temperature.	Failure rate Useful life

Useful life

In some types of plastic-encapsulated transistors, certain electrochemical effects (associated with the plastic material itself and its interaction with the transistor components) give rise to a potential wearout reliability characteristic. This is strongly temperature-sensitive, and the manufacturer's ratings are such that the wearout region is not approached when the device is used under the usual conditions and for the normal duration. Where an application requires an exceptionally long life, or continuous operation at temperatures in the vicinity of the maximum, then Figs.6 and 7 show the style of the relationship between useful life and junction temperature.

In Figs.6 and 7 the useful life of two distinct families of Mullard plastic-encapsulated transistors is plotted against junction temperature. For convenience only, the end of useful life is arbitrarily defined here as occurring when the failure rate exceeds 5×10^{-6}/h. Fig.6 is for small-signal transistors rated at 350mW (Ref.3); Fig.7 is for 1W transistors which incorporate an improved bonding system recently introduced by Mullard (Ref.4).

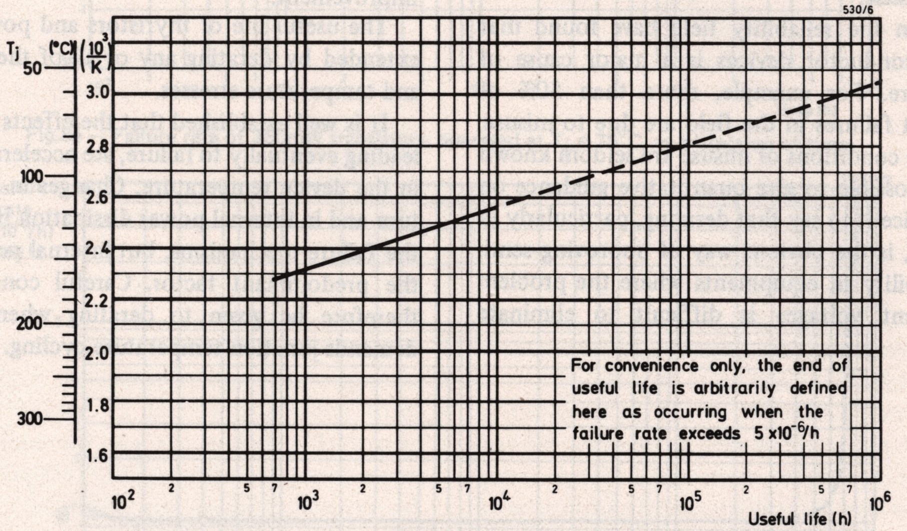

Fig.6 — Guide to the useful life of 350mW small-signal plastic-encapsulated transistors: junction temperature against useful life

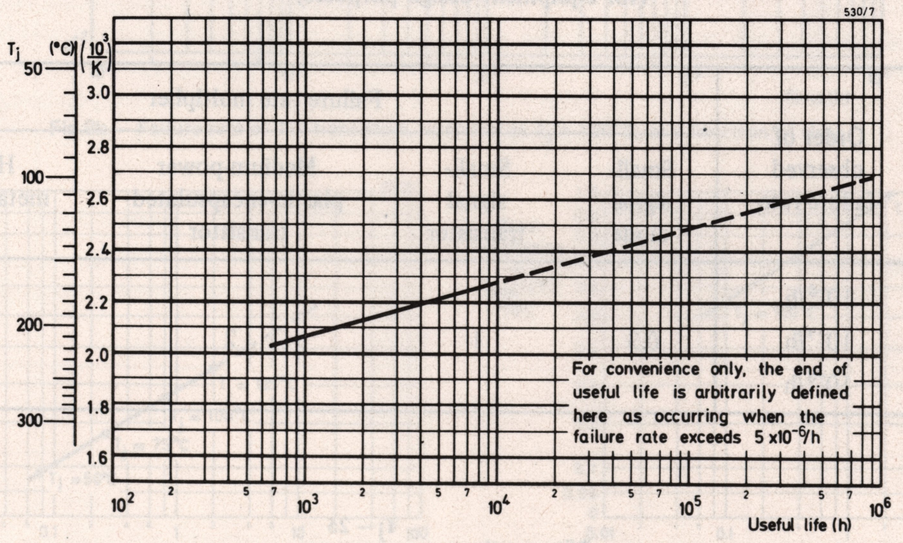

Fig.7 — Guide to the useful life of 1W plastic-encapsulated transistors: junction temperature against useful life

Failure rate

Reliability data from endurance tests and from the field, on a wide range of Mullard transistors, show that the factors given in Table 3 may be used as a guide to the relationship between junction temperature and failure rate. The factors are based on the consideration of junction temperatures only but, as already indicated, this is for most devices the most critical parameter affecting reliability. This table assumes, as does MIL-HDBK-217B, that the required life is less than the wearout life and that field failures due to misuse are neglected.

The differences in device technology, which give rise to differences in the response of the device to derating, mean that Table 3 can be used only as a general guide. In practice, different factors may be appropriate for individual types of device within the same category.

For the two families of plastic-encapsulated transistors considered earlier, failure rate is examined in Fig.8. Figs.8a and 8b show, for 350mW and 1W transistors respectively, failure rate against time under realistic working conditions: average junction temperatures of 75°C (Fig.8a) and 100°C (Fig.8b). In Figs.8c and 8d, power dissipation is plotted against failure rate, with the corresponding junction temperature values marked on the curves.

Sensitivity to misuse

Many workers in the reliability field have found that misuse of semiconductor devices is a major cause of equipment failure. For example, more than 50% of integrated circuit failures in the field are due to misuse, but as the precise conditions of misuse are seldom known it is almost impossible to give quantitative guidance on the subject. Suffice it to say that derating, particularly in terms of voltage, is the obvious way of improving semiconductor reliability in equipments where the problem of high transient voltages is difficult to eliminate completely.

Thyristors and power diodes

The derating information given below is based largely on the results of laboratory life-tests. An alternative source of information for the component manufacturer can be reliability reports from users; that is, field data. The latter, however, is difficult to obtain and can be inaccurate. In the laboratory, life-tests can be carried out under strictly controlled conditions (although at considerable expense of equipment, manpower, and electrical energy). Test results are analysed and statistically related to factory production programmes, and overstress tests are carried out to establish the incidence of fatigue defects. The analysis of failed devices is an important part of the Mullard scheme for product assessment and improvement.

The useful life of thyristors and power diodes can be extended by derating any or all of the voltage, current, and temperature stresses.

It is well established that the effects of device defects, leading eventually to failure, are accelerated by variations in the device temperature. Changes in ambient temperature and in internal power dissipation both contribute to the failure mechanisms, but internal power dissipation is the predominant factor. Careful consideration should therefore be given to derating when the application demands junction temperature cycling.

TABLE 3

Guide to Diode and Transistor Failure Rates Related to Temperature Stress

(for equipment design purposes)

Stress ratio*	Order of observed failure rate	Failure rate multiplier			
		Small-signal diode	Small-signal transistor	Medium-power plastic-encapsulated transistor	High-power metal-encapsulated transistor
0.9 to 0.7 0.7 to 0.3 <0.3	10^{-6}/h 10^{-7}/h 10^{-8}/h	0.3	1	2	4

$$\text{*Stress ratio} = \frac{T_j - 25}{T_{j(max)} - 25}$$

where T_j is the nominal operating junction temperature and $T_{j(max)}$ is the maximum rated junction temperature (°C).

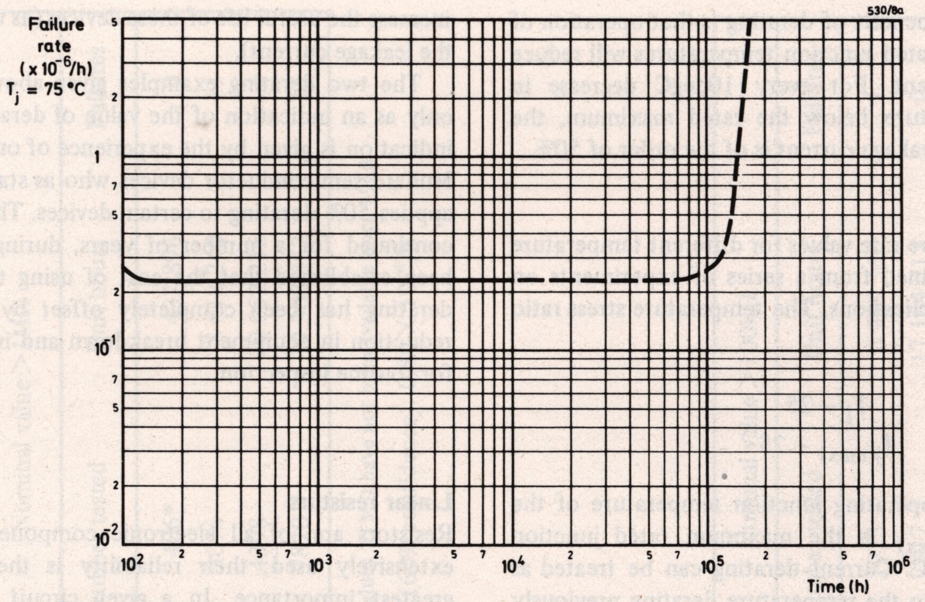

Fig.8a — Failure rate of 350mW transistors, operated at T_j = 75°C, as a function of time

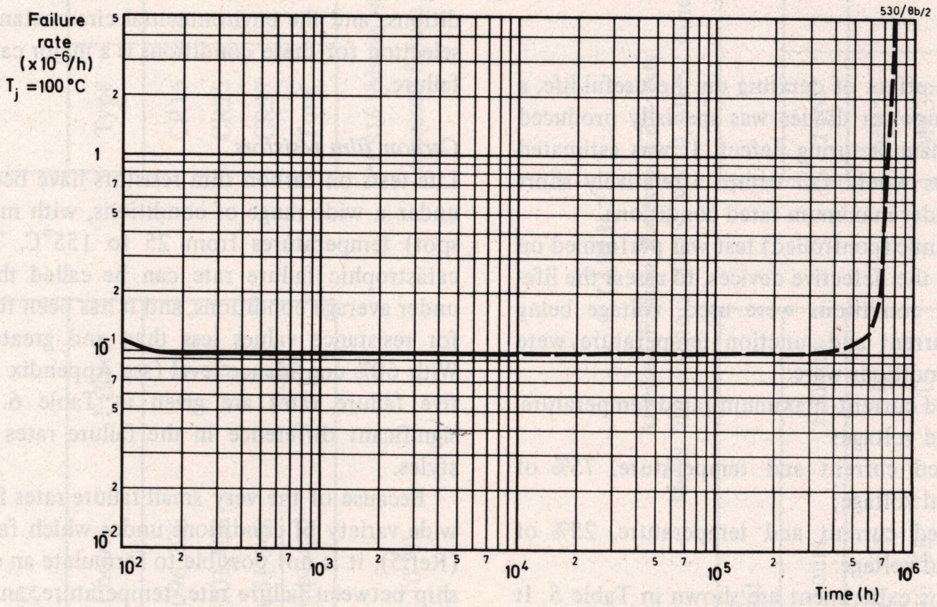

Fig.8b — Failure rate of 1W transistors, operated at T_j = 100°C, as a function of time

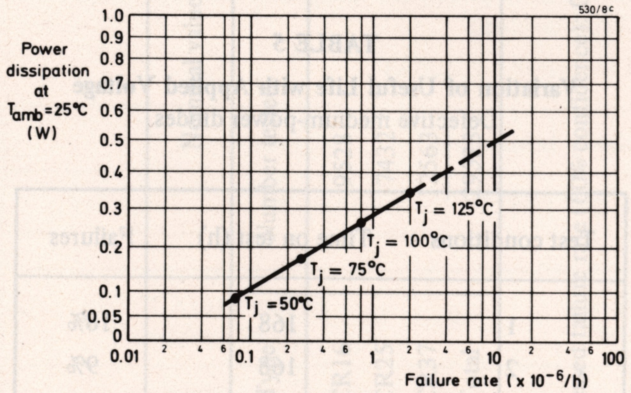

Fig.8c — Derating curve for 350mW transistors: power dissipation against failure rate

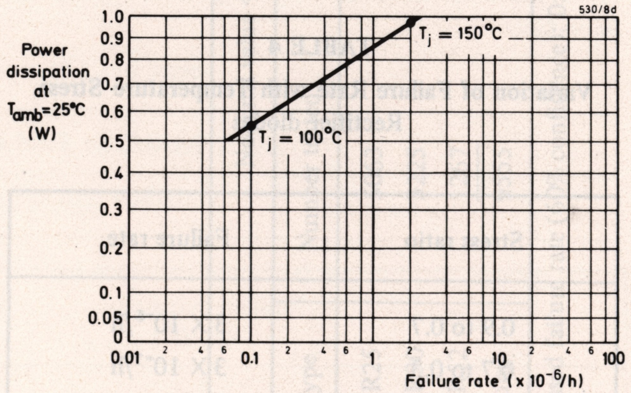

Fig.8d — Derating curve for 1W transistors: power dissipation against failure rate

An additional benefit of derating is that operation of the devices at derated junction temperatures will reduce the leakage current. For every 10degC decrease in junction temperature below the rated maximum, the reduction of the leakage current is of the order of 50%.

Failure rate

Table 4 gives failure rate values for different temperature stress levels, obtained from a series of experiments on rectifiers in tv applications. The temperature stress ratio is defined as:

$$\frac{T_j - 25}{T_{j(max)} - 25},$$

where T_j is the operating junction temperature of the device, and $T_{j(max)}$ is the maximum rated junction temperature, in °C. Current derating can be treated as similar in effect to the temperature derating previously explained.

Useful life

To determine the effect of derating on the useful life, a batch of medium-power diodes was specially produced with a known manufacturing defect. It was estimated that these devices would fail within a relatively short time when run under maximum rated conditions.

A simple dynamic (controlled) test was performed on a large sample of the defective devices, to assess the lifetime. Three test conditions were used, voltage being variable while current and junction temperature were fixed. The test conditions were:

1) maximum rated current, maximum rated temperature, maximum rated voltage;
2) maximum rated current and temperature, 75% of maximum rated voltage;
3) maximum rated current and temperature, 25% of maximum rated voltage.

The results of this experiment are shown in Table 5. It can be concluded that voltage derating can significantly increase the useful life of these devices (as well as reducing the leakage current).

The two derating examples given above can be used only as an indication of the value of derating. A further indication is given by the experience of one large user of Mullard semiconductor devices who as standard practice applies 50% derating to certain devices. This practice has continued for a number of years, during which it has been established that the cost of using this amount of derating has been completely offset by the resultant reduction in equipment breakdown and in the necessity for routine inspection.

Linear resistors

Resistors are, of all electronic components, the most extensively used; their reliability is therefore of the greatest importance. In a given circuit the reliability depends on the quality of the resistors, the operating conditions, and the environmental circumstances; improper selection for these conditions is a major cause of resistor failure.

Carbon film resistors

Life-tests on carbon film resistors have been carried out under a wide range of conditions, with maximum (hot-spot) temperatures from 25 to 155°C. The aggregate catastrophic failure rate can be called the failure rate under average conditions, and it has been found different for resistance values less than and greater than 1MΩ. With 60% confidence level (see Appendix 3), the respective failure rates are given in Table 6. There is no significant difference in the failure rates for the three styles.

Because of the very small failure rates found, and the wide variety of conditions under which failure occurred (Ref.5), it is not possible to formulate an exact relationship between failure rate, temperature, and loading; the results do indicate that any such relationship will not be

TABLE 4

Variation of Failure Rate with Temperature Stress

Rectifier diodes

Stress ratio	Failure rate
0.9 to 0.7	3×10^{-6}/h
0.7 to 0.3	3×10^{-7}/h
<0.3	3×10^{-8}/h

TABLE 5

Variation of Useful Life with Applied Voltage

Defective medium-power diodes

Test conditions	Time on test (h)	Failures
1	168	18%
2	168	9%
3	1000	0

TABLE 6

Assessed Failure Rates in Life-tests

Carbon film resistors CR16, CR25, CR37 series

Nominal value <1MΩ			
Type	Number tested	Unit hours	Failures
CR16	9528	24 096 376	2
CR25	7432	37 201 408	6
CR37	12563	50 651 648	3
Total	29523	111 949 432	11

Assessed failure rate (60% confidence) 0.11×10^{-6}/h

Nominal value >1MΩ			
Type	Number tested	Unit hours	Failures
CR16	406*	437 896	0
CR25	3016	8 818 240	11
CR37	4398	10 052 216	4
Total	7820	19 308 352	15

*CR16 resistors with values >1MΩ have not been available since 1968

Assessed failure rate (60% confidence): 0.80×10^{-6}/h

TABLE 7

Assessed Failure Rates in Life-tests

Metal film resistors MR25, MR30, MR52 series

Nominal value <100kΩ			
Type	Number tested	Unit hours	Failures
MR25	5063	18 114 504	0
MR30	3225	9 340 168	0
MR52	1267	3 304 504	0
Total	9555	30 759 176	0

Assessed failure rate (60% confidence) 0.03×10^{-6}/h

Nominal value >100kΩ			
Type	Number tested	Unit hours	Failures
MR25	1973	6 989 360	1
MR30	2917	17 164 712	0
MR52	1097	2 409 512	0
Total	5987	26 563 584	1

Assessed failure rate (60% confidence): 0.08×10^{-6}/h

Assessed failure rate for all values (60% confidence): 0.04×10^{-6}/h strong. It is not, therefore, possible to obtain from these results any derating formula or curve.

The failure rates are in accordance with those given in MIL-HDBK-217A (Ref.2) for resistors to specification MIL-R-10509D, which are similar in construction to the Mullard CR series. The failure rate factors in MIL-HDBK-217A may therefore be applicable.

Metal film resistors

The results of life tests carried out on metal film resistors are shown in Table 7. Failure rates are seen to be extremely low, and there is no significant difference between the failure rates of the various values and types.

Since only one failure occurred (after 10 000h at a hot-spot temperature of 145°C), it is not possible to quote a failure rate dependent on temperature, load, or test duration.

Field reliability information

The failure rate of a component under field conditions (that is, the conditions under which the component is designed to operate), potentially very useful information, can be estimated only if complete details of operating times and failures are available. The information in Table 8 relates to the application of CR and MR series resistors in five types of communication equipment over a number of years.

The components were operated at fairly stable temperatures, rarely exceeding 40°C; in most cases the humidity was normal. Circuit design is based on the recommended power rating for the resistors up to ambient temperatures of 45°C, above which temperature they are derated linearly to zero at 90°C.

The overall field failure rates shown in Table 8 are exceptionally low. The equipment monitored was, of course, designed for maximum reliability and the components have been derated and used under moderate climatic conditions. The laboratory and field performances discussed in this section indicate that the reliability of Mullard carbon film resistors is more than adequate for applications in which reliability is of paramount importance.

Capacitors

Capacitors form about a quarter of the components used in electronic equipment. About one-seventh of all equipment failures are due to capacitor failures; and about half of all capacitor failures are caused by incorrect selection and use. These figures highlight the importance to equipment manufacturers of capacitor quality and reliability, and also emphasise the need for an appreciation of capacitor failure mechanisms.

Polyester capacitors

Polyester capacitors are extensively used in both consumer and industrial equipment, and extensive life tests have shown an extremely high standard of performance and reliability. The failure percentages and failure rates shown in Figs.9 and 10 relate to a continuous operating temperature of 85°C and, to obtain accelerated results, to 1.5 and 2.0 times the nominal voltage. These results are for 400V range C296 series capacitors.

Fig.10 clearly shows that the failure rate is greatest during the first 100 hours, and then falls significantly.

In Table 9 the results of life-tests on the C296 series capacitors are given more fully. Capacitors are considered to have failed if one or more of the following have occurred:

1) a short-circuit through a perforation in the dielectric;
2) a change in capacitance of more than 5% of the specified initial value;
3) an increase in the loss factor (tan δ) beyond the specified initial value;
4) a decrease in insulation resistance (measured at 20°C) greater than the specified initial value.

The failures indicated in Table 9 are due entirely to a short-circuit. No low-value capacitor failed. With high values of the 160V range even after 10 000 hours at twice the rated working voltage, the percentage of failures is still smaller than 4%. With high values of the 400V range at twice the rated voltage, the percentage of failures appears to be high (42%). This is because the capacitance is proportional to the length of the film; and the longer the film, the greater the change of a weak spot or pinhole being included.

TABLE 8 Field Reliability Information

Carbon film and metal film resistors

Type	Number in operation ($\times 10^3$)	Unit hours ($\times 10^9$)	Failures	Failure rate ($\times 10^{-6}$/h) (60% confidence)
Carbon film	5725	130	3	0.00003
Metal film MR25	7.5	0.162	0	0.006

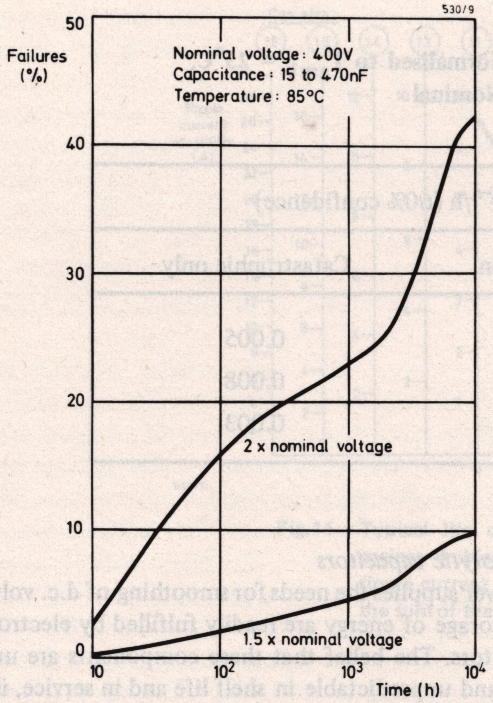

Fig.9 — Percentage of failures as a function of time (polyester capacitors)

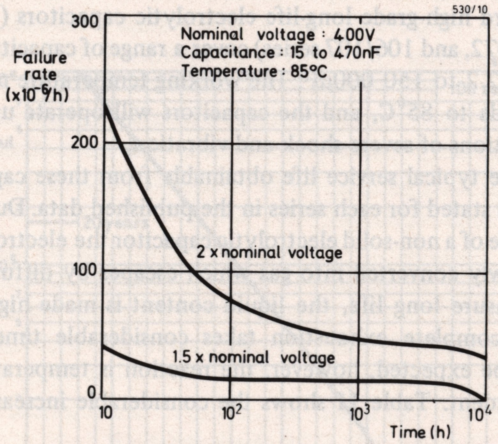

Fig.10 — Failure rates as a function of time (polyester capacitors)

It has been formulated that the average service life of a capacitor is inversely proportional to a power x of the voltage applied. Hence if L_1 is the average service life at voltage V_1, and L_2 is that at voltage V_2, then:

$$\frac{L_2}{L_1} = \left(\frac{V_1}{V_2}\right)^x,$$

where the exponent x generally has a value between 4 and 6.

For the C296 series, the value of x can be calculated by comparing the test results at 1.5 times the rated voltage and at twice the rated voltage.

For the 400V components, the number of failures at twice the rated voltage is approximately four times the number at 1.5 times the rated voltage. Thus:

$$\left(\frac{2}{1.5}\right)^x = 4,$$

whence x is approximately 5. This means that the service life of polyester capacitors is inversely proportional to the fifth power of the voltage applied. Consequently, at the rated voltage we may expect the failure rate to be smaller than at 1.5 times the rated voltage, by a factor of $(1.5)^5$; that is, nearly 8.

For 160V types the failure rate at the nominal voltage will be less than 0.02% per 1000h; that is, 0.2×10^{-6}/h. For higher-value 400V types it will be approximately 0.1% per 1000h or 1×10^{-6}/h.

While these figures for the C296 (extended-foil) series indicate a significant improvement in reliability over capacitors using paper as the dielectric, it should be realised that all the failures are due to perforation of the dielectric. In a construction that uses metallised plastic film (such as the C280, C281, and 344 series) however, a short-circuit through the film is unlikely to cause failure. Any minute pin-holes in the dielectric are 'burnt-out' by a process known as healing, thus preventing failure. Healing is automatic: if a voltage is applied to the capacitor, and current flows through the short-circuit, then the

TABLE 9 Survey of Failures of C296 Series

Component		Number of failures (%)			
Voltage	Capacitance	1.5 X rated voltage		2 X rated voltage	
		1000h	10 000h	1000h	10 000h
160V	10 to 22nF 33nF to 1μF	0 1.5	0 2.3	0 2.4	0 3.8
400V	1 to 10nF 15 to 470nF	0 3.3	0 9.4	0 22	0 42

TABLE 10

Failure Rates of Metallised Film Capacitors Normalised to T_{amb} = 25°C, Voltage Load 100% of Nominal

Component	Failure rate × 10^{-6}/h (60% confidence)	
	Catastrophic + degradation	Catastrophic only
C280 series	0.013	0.005
C281 series	0.021	0.008
344 series	0.010	0.003

current density at the pin-hole fault will be extremely high and metallising aluminium will be evaporated in the region of the fault. Thus the short-circuit is cleared and the capacitor restored to its specification.

As with the C296 series, failures defined by the other rejection criteria (insulation resistance, tan δ, and capacitance-stability) are too low to permit a useful interpretation. Consequently the failure rates of the metallised film capacitor must be appreciably better than those for the foil capacitors. For metallised film capacitors of the C280, C281, and 344 series, Table 10 gives failure rates obtained from accelerated tests and normalised to 25°C and nominal voltage. Both catastrophic (open- and short-circuits) and degradation failure rates are given. The criteria for degradation failure are:

1) a change in capacitance greater than twice the specified value at 1000h;
2) loss factor (tan δ) greater than twice the specified value at 1000h; or
3) insulation resistance less than 0.1 times the specified value at 1000h.

Electrolytic capacitors

In power supplies the needs for smoothing of d.c. voltages and storage of energy are readily fulfilled by electrolytic capacitors. The belief that these components are unreliable, and unpredictable in shelf life and in service, is out of date; if a particular range of capacitors is properly manufactured using the latest techniques, then correct selection from within that range can ensure long life. The Mullard high-grade long-life electrolytic capacitors (108, 071/072, and 106/107 series) cover a range of capacitance from 2.2 to 150 000μF. The working temperature range extends to 85°C, and the capacitors will operate under conditions of severe shock and vibration.

The typical service life obtainable from these capacitors is stated for each series in the published data. During the life of a non-solid electrolytic capacitor the electrolyte is slowly converted into gas which escapes by diffusion. To ensure long life, the liquid content is made high so that complete exhaustion takes considerable time; as may be expected, the reaction is temperature-dependent. Table 11 shows the considerable increase in service life obtainable by operation of capacitors at reduced ambient temperatures.

TABLE 11 Life Expectancy of Mullard Long-life Capacitors at Various Ambient Temperatures

Long-life series	Operating temperature		
	85°C	40°C	25°C
071/072	>5000 hours (>0.5 year)	>80 000 hours (≃10 years)	>130 000 hours (≃15 years)
106/107	>5000 hours (>0.5 year)	>80 000 hours (≃10 years)	>130 000 hours (≃15 years)
108	>10 000 hours (>1 year)	>160 000 hours (≃20 years)	

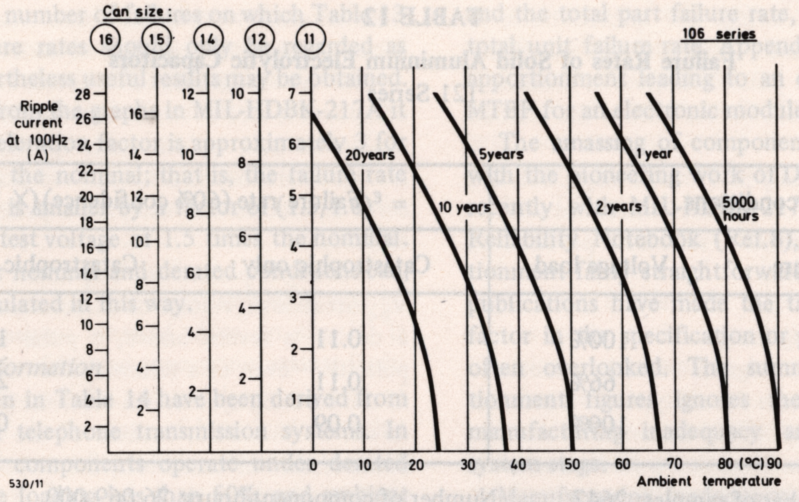

Fig.11 – Typical life of capacitors in the 106 series plotted against ambient temperature and ripple current. The ripple current is measured at the rated voltage, which is the sum of the direct voltage and the peak ripple voltage

The ripple current through a capacitor also affects the life, because of the heating effect on the component. Each capacitor has a rated maximum ripple current, determined principally by the permissible power dissipations of the capacitor surface area. The ripple current rating is usually quoted at 100Hz. At 50Hz the rating is reduced to 0.7 times the 100Hz rating. At frequencies above 10kHz, the rating may be increased by 20% or more.

For the 106 series the working life is related to ripple current, can size, and ambient temperature as shown in Fig.11. For smaller capacitors, ripple current has less effect on the life, and the curve of Fig.12 indicates life expectancy against ambient temperature for the 108 series of capacitors.

Further information on the 108, 071/072, and 106/107 series of high-grade long-life capacitors is given in Ref.6.

For solid-electrolyte capacitors (121 series), long-term life-tests have been carried out and detailed results and predictions are available. They are presented here in summarised form, and distinction is made between catastrophic failures (that is, open- or short-circuits) and degradation failures. The criteria for degradation failure are:

1) change in capacitance exceeding 30% negative or 25% positive;
2) loss factor (tan δ) greater than 1.5 times the specified requirement;
3) impedance greater than 1.5 times the specified requirement; or
4) leakage greater than 5 times the specified requirement.

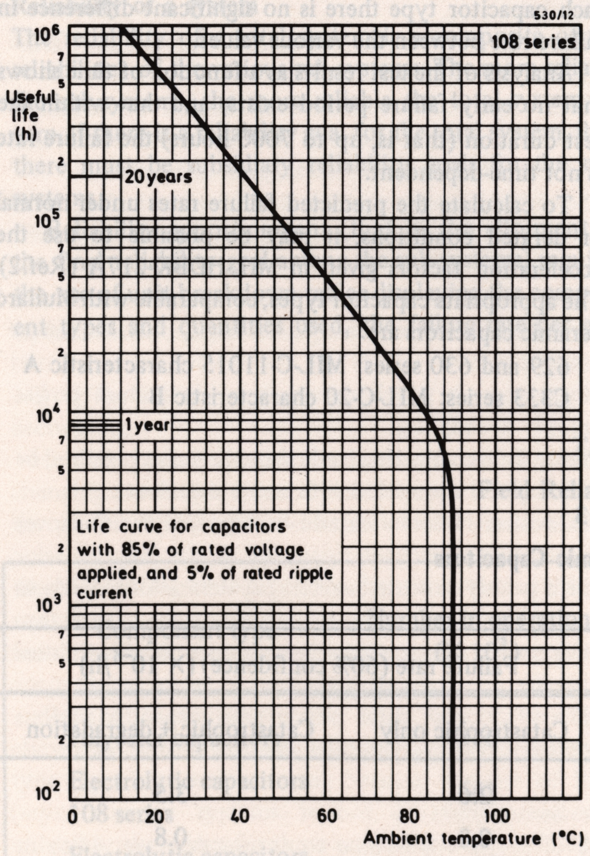

Fig.12 – Typical life of capacitors in the 108 series plotted against ambient temperature

TABLE 12

Failure Rates of Solid Aluminium Electrolytic Capacitors

121 Series

Test conditions		Failure rate (60% confidence) ($\times 10^{-6}$/h)	
Ambient temperature	Voltage load	Catastrophic only	Catastrophic + degradation
85°C	100%	0.11	1.9
85°C	66%	0.11	2.0
25°C	100%	0.09	0.2

Number of samples: 2647 Number of component-hours: 26 069 000

The failure rates under three different conditions are given in Table 12. No catastrophic failures occurred in a total of about 26 million component hours. Of the total of 30 degradation failures, 20 were due to either impedance or loss factor increases. There was no significant difference between the failure rates for capacitors of different values and voltages.

For the tests carried out at 85°C the failure rate varies with time, showing a pronounced increase after 7000h (very few failures occurred before this time). The failure rate rises from 1.5×10^{-6}/h at 7000h, to about 9×10^{-6}/h at 10 000h: this applies to the tests at nominal load and at 66% of nominal load. For the tests at 25°C and nominal load, the failure rate is constant until at least 10 000h.

Ceramic capacitors

Life-tests on Mullard ceramic capacitors have given the estimated failure rates set out in Table 13. Catastrophic failures are open- or short-circuits; degradation failures are defined by:

1) a change in capacitance greater than twice the requirement after 1000h;
2) loss factor (tan δ) greater than twice the requirement after 1000h; or
3) insulation resistance less than 0.1 times the requirement after 1000h.

The tests were all performed at maximum permissible ambient temperature and a 50% voltage overload. For each capacitor type there is no significant difference in failure rate between the various values.

Analysis of the test results as a function of time shows that no early failure period exists, and that within the test duration (that is, up to 7000 hours) the failure rate is not time-dependent.

To calculate the predicted failure rates under normal or derated conditions, it may be possible to use the acceleration factors given in MIL-HDBK-217A (Ref.2). The appropriate capacitor types, comparable with Mullard ceramic capacitors are:

629 and 630 series: MIL-C-11015 characteristic A
C333 series: MIL-C-20 characteristic B

TABLE 13

Failure Rates for Ceramic Capacitors

Type	Test conditions		Failure rate (60% confidence) ($\times 10^{-6}$/h)	
	Ambient temperature	Voltage load	Catastrophic only	Catastrophic + degradation
629 series	55°C	150%	2.6	3.5
630 series	85°C	150%	0.8	0.8
C333 series	85°C	150%	0.7	6.5

Owing to the small number of failures on which Table 13 is based, the failure rates should only be regarded as approximate. Nevertheless useful results may be obtained. By extrapolation from the graphs in MIL-HDBK-217A it is seen that the acceleration factor is approximately 3 for voltages exceeding the nominal; that is, the failure rate at nominal voltage is smaller by a factor of $(1.5/1.0)^3 = 3.375$ than at the test voltage of 1.5 times the nominal. Failure rates under nominal and derated conditions can, if required, be calculated in this way.

Field reliability information

The field data given in Table 14 have been derived from failure analysis in telephone transmission systems. In these systems the components operate under derated conditions: voltage loading less than 50%, and ambient temperature about 40°C. The failure criteria are:

1) open- or short-circuit; or
2) a drift in the component characteristic considerably larger than the requirement.

Because of differences in the failure definition, the failure rates given here are not directly comparable to those derived from life-tests. They show, however, the performance obtainable from systems designed for reliability.

Reliability of a system

The reliability of a total system is a composite of the reliabilities of the various sub-systems. The more reliable the sub-systems, the more reliable the total system. In turn, if there is a reliability goal for the total system, then there must be subsidiary reliability goals for the sub-systems.

Reliability apportionment (that is, the allotment of the final reliability goal among the sub-systems) requires the use of unit breakdown tables displaying the component types and quantities used, the failure rate per part and the total part failure rate, which are combined in a total unit failure rate. Appendix 4 shows the reliability apportionment leading to an estimated failure rate and MTBF for an electronic module.

The amassing of component reliability data, starting with the pioneering work of Dummer (Ref.7), and more recently with MIL-HDBK-217 (Ref.2) and the RADC Reliability Notebook (Ref.8), makes reliability apportionment fairly straightforward. However, because these publications have made the task easier, one important factor in the specification or prediction of reliability is often overlooked. The summation from the apportionment figures ignores the hazards introduced by manufacturing inadequacy and design error at the system stage.

Manufacturing inadequacy includes poor workmanship and processing, and inspection and testing errors. Design errors include component over-rating, misguided targeting by the component user (and unknowing acceptance of this by the supplier), and misuse.

A principal feature of the Mullard quality assurance system (insofar as it relates to building-in, measuring, and reporting reliability) is the extent of its control over the disciplined design and manufacture of Mullard products. The detailed functions of the system include:

1) creating a device target specification which is fully comprehensive in its coverage of device characteristics, and complies with the requirements of the customer;
2) overseeing the design at the earliest possible stage, to provide a second opinion on all aspects of the design that relate to good practice;
3) providing information to designers on new, standard, and preferred components, materials, and specifications, and ensuring their use;
4) evaluating the performance and reliability of the product and its components and processes for release, through realistic engineering tests;

TABLE 14

Field Reliability Information

Component type	Number in operation ($\times 10^3$)	Component hours ($\times 10^9$)	Failures	Failure rate 60% confidence ($\times 10^{-6}$/h)
Polyester capacitors	516	11.8	4	0.00045
Electrolytic capacitors 108 series	641	15.8	28	0.0019
Electrolytic capacitors 121 series	35	0.562	0	0.0016

5) scrutinising the final drawings and specifications, to ensure that the acceptance quality level is stated and to locate and eliminate possible sources of manufacturing and production difficulties before the start of bulk production;
6) ensuring that the necessary methods of inspection and testing are available before production commences;
7) carrying out the mechanisms of release for production;
8) providing user information.

Source of data for derating design

Hard-pressed equipment designers would welcome a simple set of derating figures for all types of electronic components related to the principal factors in the various applications. Ideally such a document would embrace all effects on reliability such as the style of construction, the manufacturer, variations in the nominal operating conditions, and the definition of what constitutes failure. Unfortunately these factors usually have a first-order effect on reliability, and when to this is added the major contribution which misuse makes to the apparent reliability characteristic in ultimate use, it is clear that the benefits of derating are most likely to be achieved by bilateral contacts between the component maker and the equipment designer.

ENVIRONMENTAL EFFECTS ON RELIABILITY

Having made a choice of components for low failure rate and long life, it is necessary to ensure that the environment in which the components are to operate is conducive to good reliability of both components and equipment. That is, the environment must be such that:
1) the reliability of the components is maintained, and
2) the equipment operates correctly.
It is likely that similar measures will achieve both these aims; in any event the aims will not be found to be conflicting.

The term 'environment' in this context will include both the local and the general environments of the component; that is, equipment power supply circuits and connections, component layout, signal and control function paths, heatsinks, mechanical considerations, etc., as well as the ambient conditions in which the equipment is to operate.

Layout and earthing

Equipment layout will normally follow the logical sequence of circuit functions, and whenever possible a complete circuit function should be included on a single panel. This improves operational reliability by minimising the injection of interference and transients from other stages of the equipment, and by eliminating the necessity for plug-and-socket connections or edge connectors within the circuit. Furthermore, the possibility of accidental disconnection of one part of the function from another, with the attendant hazard to component life as a consequence of over- or under-driving, is avoided.

The layout should also avoid interaction between components and between circuits, and special attention should be paid to the earth system. Cases have been known where investigation showed that an inconspicuous earth conductor was carrying a peak current of several amperes.

Earthing is particularly important because of the low V_{be} breakdown voltage of semiconductor devices. Where a device is reverse-biased, a pulse of the appropriate polarity – even of a relatively low amplitude – induced in the earthing system can send the junction into breakdown. Furthermore, because of the very large 'mutual conductance' of transistors, the circuit operation can be upset by any disturbance in the earth rails.

Equipment earthing is therefore considered at the design stage. For example, the return lead from the power supply reservoir capacitor will be taken directly to the source of a.c. supply, and connection to the rest of the equipment made at one point only. Nevertheless it is possible for errors to be made when the equipment is assembled, and the effects produced may be mysterious. A large transient earth current flowing in a printed conductor will give rise to an appreciable voltage drop, compared with a transistor V_{be}, causing faults which are difficult to trace.

The following very simple rules for layout and earthing have been formulated.
1) Each significant current loop should be returned direct to the source via its own earth lead, and connected to the common earth at one point.
2) Sensitive circuits, such as the reference voltage and error-amplifier in a power supply, should be mounted closely together.
3) Each circuit panel should have its own earth rail, connected at one point to the equipment common earth point.
4) Each circuit panel should have individual power supply decoupling.
5) Long interconnecting leads should, where possible, be decoupled or provided with series impedance.
6) Television receivers should incorporate the flashover protection scheme.

While a poorly executed earthing system seldom leads to catastrophic failure, there are grounds for the supposition that it can be a source of otherwise inexplicable failures during life.

The practice of these points with respect to various component types and circuits will now be discussed.

Television circuits

It is of prime importance to ensure that any wires or cableforms carrying control potentials or signals associated with semiconductor circuits are kept away from the picture tube. The external Aquadag coating and the rimband of the picture tube can be dangerous sources of flashover energy. The panel carrying the channel-selection mechanism and receiver controls, in particular, should not be closely adjacent to the band: a clearance of at least 30mm between such metalwork and the band is recommended, and the control wiring must be positively located in such a way that it cannot come close to any part of the picture tube or EHT cable.

Where a long control lead originates from an integrated circuit, a series resistor situated close to the IC is recommended as an additional precaution against flashover effects. For normal d.c. control leads, a value of 1kΩ is appropriate. In the case of long leads carrying pulses or signals, a lower value may be necessary to avoid waveform distortion. Provided that the leads in such cases are not excessively long, a value of 100Ω gives useful protection.

TTL integrated circuits

For best performance, each panel should bear an earthed ground plane. Where complex interconnection on double-sided boards makes this impossible to achieve, a ground bus line must run round the outside edge of each panel. Each end of each line should be returned to a common point or to a system ground.

MOS integrated circuits

From isolated MOS circuits among large arrays of TTL logic, the use of MOS has increased so that now whole panels and even complete systems are built of MOS ICs. The majority of the large MOS arrays are memory functions, but with the advent of the programmed logic array (PLA) this situation will change. The memory system is synchronous, with a large number of 'clock' lines interconnecting the ICs, while the PLA system is asynchronous. Layout and power supply design for the two types of system will be similar, but the systems will differ in the necessary approach to earthing and decoupling.

In the synchronous system the numerous clock lines changing state simultaneously constitute a heavy load on the power supply and necessitate careful precautions if noise-margins are to be maintained: the system could therefore be regarded as 'worst-case'. Nevertheless if in an asynchronous system, simultaneous 'clocking' occurred fortuitously at a particular instant, then the problems encountered might be even more severe.

Reliability discussions for MOS arrays, here and elsewhere in this article, will refer only to memory-type (synchronous) systems, because the use of PLA (asynchronous) systems is not yet widespread and reliability guidelines for them are not yet well-defined.

Opinions differ concerning the desirability of boards with ground- and power-planes, rather than with interconnections on both sides. There is evidence that the 'plane' system offers superior noise suppression within the system, but double-sided boards can be used if the power supply layout on the board is such that there is a 'grid' arrangement, and if there is adequate decoupling (which will be discussed later).

Any TTL signals in the system should be kept remote from MOS power leads which carry heavy surge currents, and from MOS signal leads which carry pulses whose edges have a relatively large energy content. (These effects are due to the capacitative nature of MOS inputs.) Electrical separation can be achieved at the TTL/MOS interface circuits.

In MOS arrays, especially memories, because of layout symmetry it is possible to obtain a greater packing density than could be achieved in a TTL logic array. Care must be taken to ensure adequate ambient temperature control, as increased operating temperatures lead to reduced device life, and increased unreliability.

Power supplies and decoupling

The design of the equipment power supply must ensure that the required voltage is maintained under a wide range of conditions. In particular, the spread in current demand of the components of the equipment must be considered. It is also necessary to examine the possible fault conditions, ensuring that the power supply will fail safe; that is, will not cause secondary failure of the equipment.

Television integrated circuits

The design of television integrated circuits allows at least a ±10% voltage range over which correct operation is maintained. As a general design approach most of the signal amplitudes, d.c. levels, and control functions associated with each integrated circuit track proportionately with voltage. However, in a receiver with well-stabilised picture tube supply potentials, an operational variation of ±10% in supply voltage to the integrated circuits is likely to result in unacceptable picture variations. Because of operational variations of mains voltage, ambient temperature, and picture tube beam current, an l.t. supply having a voltage stability tolerance of ±3% is recommended to ensure a high degree of picture stability. In any design, however, the operational variations, added to the set-to-set spread in supply voltage, should lie within ±10% of the nominal supply voltage.

Unlike groups of discrete components, where the total supply current is the result of an average of the effects of a number of components, all the components of the same kind in an integrated circuit can vary above or below the nominal case together. Integrated circuits of a given type exhibit a tolerance in required supply current (at a constant voltage) which may be as high as ±25%.

In a system comprising several integrated circuits there is therefore the possibility of considerable variation in total current demand from one assembly to another. This must be allowed for in the design of the power supply circuit.

An l.t. supply of from 20 to 40V is usually available in an all-transistor receiver, and it is convenient to provide the power for the integrated circuits from this. The requirement for good tracking of the supply potentials to each integrated circuit, together with the tolerances in current demand for each one, generally precludes the operation of the integrated circuits from the l.t. rail via individual voltage-dropping resistors. Furthermore, similar operation but with a common voltage-dropping resistor would also be unacceptable because of the possibility of a combination of one high-current integrated circuit with a number of low-current ones. The result could be that the voltage across all the circuits would be considerably higher than nominal, and that excessive power dissipation could occur in the high-current circuit.

These conditions lead to the requirement for:

1) a simple supply source having adequate voltage stability and low impedance, or
2) a resistor feed with a single parallel voltage reference diode connected across the integrated circuits, or
3) a series stabiliser employing a transistor with a voltage reference diode.

For (1) a direct scan-rectified 12V supply could be obtained from the line output transformer in an all-transistor receiver. Such a supply would have voltage variations due to beam current of typically 0.6V for 90° deflection circuits and 0.3V for 110°. However, a diode, an electrolytic capacitor, and an extra transformer tap would be required as well as flashover protection components, and so this is not necessarily the most attractive solution. For (2) a single voltage reference diode of about 1W dissipation would be required with a ±5% voltage tolerance, and for (3) a series transistor (BD131) regulated by a small voltage reference diode and possibly a preset potentiometer. Solution (2) is commonly adopted.

Although it is unlikely that power supply surges of any significance will occur during normal operation with a stabilised supply voltage, consideration must be given to the safety of the integrated circuits in the event of a possible fault condition, such as failure of the stabilising device. In the case of a parallel-connected voltage reference diode, it is unlikely that an open-circuit will be caused by damage; a short-circuit is more likely. Where a series stabiliser transistor is employed, which could, for example, be overloaded by a short-circuit on the 12V line, then a combination of a series current-limiting resistor and a transistor that will not be damaged by the surge current gives adequate protection.

Generally, the integrated circuits will not be affected by surges in supply voltage up to 50% higher than the nominal, provided that each surge is limited to about 20s duration.

Integrated circuits require the same attention to design and layout as discrete transistors to ensure adequate protection against circulating currents caused by picture tube flashover discharges. Where pulses from the line and field timebases are employed for the various gating functions, the layout of the associated networks and the types of components used must not permit the transfer of sharp voltage spikes. Similar attention must be given to the power supply network, particularly if this is derived from the line output transformer.

TTL integrated circuits

Power supplies to TTL integrated circuits must be stabilised at 5V ±5%; that is, from 4.75 to 5.25V. Operation outside these limits is possible, but the performance cannot be guaranteed. The maximum permissible voltage at the supply pins is 7.0V, but the voltage at the input pins must not rise above 5.5V.

During 1/0/1 transition (positive logic) at the output of a TTL gate, a short time exists when both transistors in the totem-pole output stage are conducting, and a current spike of amplitude up to 60mA occurs on the supply line. Spikes of this nature can cause severe interference in the system, and it is therefore necessary to decouple them. A capacitor of 0.1μF is recommended for decoupling approximately every five packages of simple TTL gates. For counters and more complex packages, a capacitor of 0.1 or 0.01μF per package is appropriate.

MOS integrated circuits

Many MOS circuits require a back-bias supply that 'sits on top' of the main power rail, to turn off the substrate diodes. Increasing this supply voltage decreases the substrate capacitance but increases the threshold voltage, and so its value must be a compromise on the part of the circuit designer. It is usually within the range from 3 to 5V. (For p-channel devices the bias supply will be more positive than the main power rail; for n-channel devices, more negative.) To prevent over-dissipation in the IC it is necessary to ensure that at switch-on the bias supply voltage rises at least as fast as that of the supply to which it is referred, and so the bias supply is generated separately in series with the main IC power supply. Superior bias supply regulation is also achieved by this method.

The current handling capability of the MOS device is limited by the bond wire and the aluminium interconnection metallisation on the chip. It may be possible therefore under failure conditions, when the bias is reversed by a fault, to limit the current by a series resistor in the bias supply lead. Under normal operating conditions very little current is drawn from the bias supply and so, provided the IC is well decoupled, such a series resistance can limit the current to about 100mA, typically the maximum that can be tolerated. Series resistance current limiting, however, does not give complete protection and so for maximum reliability some form of current limiting may be incorporated in the main power supply, or the main power supply could even be derived from the bias supply.

If the current limit protection cannot be used then a power supply crowbar may be utilised to protect against bias rail faults. A Schottky barrier diode can be used to clamp to the main power rail so that the 'forward' voltage on the substrate is less than the MOS junction diode voltage drop; an ordinary silicon diode could be substituted, but would give reduced protection.

The large peak currents demanded by MOS ICs during clock periods are the major source of unreliability. These currents are drawn from the main power supply. Because of lead inductance and other remote-supply effects, no ordinary off-board power supply could respond to the brief surges. Generous power rail decoupling across the MOS array is therefore required to eliminate the need for a power supply having very large current surge capability. One low-inductance capacitor of about 0.5μF should be provided for every five or ten MOS devices, to limit the voltage drop at the memory due to current surges to a few tenths of a volt. Decoupling capacitors should be very close to the array, or within it; no MOS device should be electrically further than 10cm from a decoupling capacitor.

Switched-mode power supplies

The switched-mode technique is increasingly used for equipment power supplies, and so some recommendations on the reliability of the switched-mode power supply itself are now given. Component failure in a power supply can cause any of the following equipment faults:

1) an obvious malfunction of the equipment: complete or partial failure, or reduced performance;
2) a change in the operating conditions of the equipment components, having a deleterious effect on their reliability;
3) a safety hazard: in a television receiver, for example, a fire risk or an increase in X-radiation.

The operation of the typical mains switched-mode power supply can be divided into four distinct processes:

1) a.c. to d.c. conversion of the mains supply;
2) d.c. to pulse power conversion, at pulse repetition rates in the range 15 to 50kHz;
3) pulse to d.c. conversion and filtering;
4) power supply control, providing automatic regulation of the output and protection against overload.

The a.c./d.c. conversion stage will comprise a mains on/off switch, a fuse, an interference filter, a current limiting resistor, a bridge rectifier, and an electrolytic filter capacitor. The average values of current and voltage associated with these components may be relatively modest: this stage of a switched-mode power supply in a colour tv receiver, for example, may provide 200W at approximately 300V. Examination of the worst-case operating conditions, however, shows that each component must be chosen with care. A peak surge current of 100A may flow in all the components, with sufficient transient energy to destroy a switch or a current limiting resistor.

The electrolytic capacitor must be carefully chosen with respect to voltage and current ratings. Under zero load conditions the voltage across this component can rise to approximately the peak value of the mains supply; the current and dissipation ratings must be compatible with the surge current mentioned above and with the steady-state ripple currents at twice supply frequency and at switching frequency. To handle the higher-frequency components an additional shunt capacitor may be necessary, but this must not create parasitic resonances.

Rectifier diodes require protection against voltage surges on the mains supply: such surges may amount to several hundreds of volts. Shunt capacitors of approximately 10nF across the bridge output will usually give sufficient protection, provided that adequate series impedance is included on the a.c. side of the bridge.

The high-frequency switching process converting the d.c. supply to pulse power may employ a power transistor operating in a ringing-choke system. Lower-power transistors or integrated circuits may be employed in the driver and control circuits. A number of semiconductor diodes will also be used, both as power rectifiers and in low-power applications. In addition to the fulfilment of the usual reliability criteria associated with the selection and operation of components in this area, a compromise must be achieved concerning the selection of the power switching transistors and diodes. If the devices are required to be rated consistently with the current, voltage, and power levels which can arise under transient and overload conditions, then prohibitively large and expensive devices are necessary. Instead, it is usual to incorporate additional circuits which absorb or diminish the high transient power levels so that the switching devices will operate within their safe operating areas under all conditions.

In a typical power supply, approximately half of the components perform functions which may be regarded as reducing the stresses which would otherwise be applied to the other components. Examples of these functions are:

1) slow start-up, to reduce surge currents;
2) overload current protection, to give protection much faster-acting than fuses;

3) overvoltage protection, to limit voltage levels under no-load or fault conditions;
4) second breakdown protection networks.

Second breakdown protection networks are LCR combinations in series or in shunt (or both) with power devices, particularly with the switching transistor but sometimes also with power rectifiers, to modify the operating loadline. For example, in the case of the switching transistor having a finite turn-off time in a circuit with inductive load, to prevent excessive dissipation it is necessary to limit the rate of rise of the voltage across the transistor during turn-off. This can be achieved with a series CR network across the transistor; an additional diode is then often used to prevent excessive turn-on dissipation due to the presence of this network.

Interconnection system

The reliability of the electrical connections in an equipment has an important bearing on the reliability of the equipment. With the increasing reliability of the components comes the need for a corresponding improvement in the interconnections between them.

The electrical interconnection system of an equipment comprises, broadly, soldered joints and connectors. Intermittent faults are often due to these items, and the tracing of such faults should never be lightly undertaken. The symptoms of a dry joint may be beyond the diagnosis of all but the most experienced.

The intermittent faults that arise from poor connections fall generally into two classes:

1) faults arising under low-voltage conditions, and disappearing when the voltage or energy available is raised;
2) faults appearing in phase with an operating condition such as temperature, humidity, voltage, or vibration.

Faults of type (1) may be either disconnections (normally caused by a dry joint across which a film of oxide slowly builds), or short-circuits and low-insulation faults caused by metallurgic effects such as silver-ion migration. Faults of type (2) are more easily traced, by taking measurements while inducing the operating condition that is associated with the fault.

Interconnection faults can not only produce the obvious disruption to service, but also contribute directly to the failure of components, particularly of active devices. An example is the line output transistor of a television receiver: it will not be harmed by a clean removal of drive, but the partial removal caused by a dry joint or faulty connector can lead to overdissipation and device destruction. Similarly, if the line deflection coils are disconnected then there will be a considerable increase in the duration of the line flyback pulse. Under normal conditions the transistor is put in conduction before flyback is completed, and the consequent high-voltage high-current operation will put the operating path outside the SOAR.

It may be that the interconnection requirements for high reliability conflict with those for ease of maintenance, service, and testing. The use of soldered joints rather than connectors for inter-board wiring will improve reliability, provided that the joints are efficiently made, but will also increase production and service costs because of the additional time necessary to assemble and test the joints, and to ensure that the connections made are correct. A solution which may be employed in a case such as that of tv line deflection coils referred to above, where components may be damaged if a connection is removed while the equipment is operating, is to wire the supply voltage to the critical stage via a pair of 'blind' pins on the connector to be protected. If these pins are made shorter than the others, then in the event of disconnection power will be removed from the circuit before the critical connection is broken.

The mounting of individual components on printed-wiring boards must be approached with an appreciation of the brittle nature of the soldered joint: it is essential that no undue mechanical stress be applied to components merely soldered to the board, during storage or operation. Mullard published data include recommendations on the mounting and handling of components.

The reliability of the soldered joint itself depends upon the nature of the metals joined. Many different metals and coatings are used for component leads, and many combinations will be encountered in an equipment. In general the best results are obtained when the leads to be soldered are pre-tinned, but if there is a considerable delay between tinning and soldering then ambient temperature and humidity during storage should be moderate, to avoid oxidation and diffusion of tin into the base metal. The solderability of Mullard components is closely controlled so that reliable joints are assured. Where special conditions are to be met, solder manufacturers should be consulted.

Contact devices such as plug-and-socket connections are often introduced into the system as an afterthought, whereas their reliability can strongly affect the reliability of the system. Failure of contact devices generally takes the form of erratic contact, causing excessive noise or temporary disconnection; it is of course possible for the temporary disconnection of a voltage level, due to a faulty contact, to cause catastrophic failure of a semiconductor device.

Before being included in an equipment designed for reliability, all connecting devices should be tested so that their performance is defined under the following conditions:

1) extreme vibration and shock;
2) high and low temperatures;
3) varying atmospheric pressures, including levels approaching vacuum;
4) exposure to corrosive elements.

Climatic conditions

The reliability of electronic equipment can be severely affected by the climatic conditions under which it is operated or stored. The equipment life can be shortened, and there can be a considerable increase in the incidence of component failure. Some component types, however, are far less vulnerable than others to the stresses imposed by severe climate, and by a suitable choice of components it is possible to improve the reliability. The manufacturer's data should be carefully studied. For most components an operating temperature range will be given, and sometimes the climatic category. These pieces of information do not define completely the severe-climatic performance of the component, but with a knowledge of the climates to be encountered by the equipment and their likely effects, it is possible to make an intelligent choice of component from the varieties available.

Mullard published data on the 015, 016, and 017 series of aluminium electrolytic capacitors, for example, states:

Climatic category (IEC Publication 68)

015 series	25/085/56
016 and 017 series	40/085/56.

The three sets of digits separated by oblique strokes correspond respectively to the temperatures, both low and high, and the number of days' exposure to damp heat, that the components will withstand, as follows:

First set	two digits denoting the minimum ambient temperature of operation (cold test) – a negative sign is assumed;
Second set	three digits denoting the maximum ambient temperature of operation (dry heat test) – where the temperature consists of a two-digit number it is preceded by a zero;
Third set	two digits denoting the number of days of damp heat the components will withstand.

The tests which the manufacturer carries out to determine the climatic category are those specified in IEC Publication 68; 'damp heat' therefore refers to IEC68-2 test Ca. Thus, to belong to the category 25/085/56, the 015 series capacitors are known to satisfy *at least* all the following tests:

1) cold (IEC 68-2 test A) −25°C,
2) dry heat (IEC 68-2 test B) +85°C,
3) damp heat, steady state (IEC 68-2 test Ca) 56 days.

The range of conditions that an equipment may encounter is nevertheless wider than the three isolated parameters listed above might suggest. The variables include temperature, moisture, biological and entomological activities, atmospheric pollution, and airborne dust. The variety of the actual conditions can be illustrated by considering three areas of different geographical type: the tropics, where high temperature and high humidity are encountered together; the desert, where the day temperature is highest and there is considerable variation between day and night temperatures; and the Arctic, where the temperature is continuously very low.

The use of modules

When an equipment is constructed from electronic modules supplied by a component manufacturer, the reliability of individual components is taken into account by the designer of the module. A custom-built module will contain components specified for the conditions under which the final equipment will operate, and the embodiment of the module will take account of the possibility of shock and vibration.

The equipment designer will, however, still have some problems to solve in assuring the reliability of the module, which can be regarded as a large, heavy electronic component. The module will have a limited range of mounting positions and may require care in handling. It will normally carry a number of electrical connections, at different voltages and currents. Modules considered in this section of the article are those for domestic applications, where low cost is important but it is essential to ensure safety and reliability in a somewhat arduous environment. The recommendations for reliability may therefore be valid for the application of electronic devices in other hazardous situations: automobiles, for example.

The module performance under a range of conditions will be specified; the peak voltage and current ratings must be observed. Normal operation will be well within the ratings but possible transient conditions must be considered. For example, operation within the peak voltage rating must be maintained in spite of:

1) mains spikes;
2) overshoots due to equipment operation;
3) surges due to the action of suppression components.

Similarly, the following will affect the peak current rating:

1) current during voltage peaks;
2) switch-on surges (perhaps very long-lasting where large motors are used);
3) stall current.

Modules are often connected to complex mechanical switching devices such as timers and programmers, which may contain several contacts making and breaking in sequence. Should this sequence not be observed then instantaneous surges or even load short-circuits may occur. Similarly, arcing in a switch may, without damaging the switch itself, instantaneously cause the module rating to be exceeded.

A major cause of failure is poor electrical connection to the module. The number of connections means that good connection design is essential. Contacts with a spring action are desirable; the non-return type of contact suitable for once-only connection is less reliable.

Where switches operate 'dry', that is where only low voltages and currents are switched, gold-plated contacts are less susceptible to oxide formation. A better solution, however, is the use of a switch with a good wiping action. In such domestic appliances as washing machines ('white goods'), the environment is generally damp, greasy, and dusty. Modules should be protected by some form of inexpensive shroud that will nevertheless not inhibit the airflow necessary for module cooling. It may be necessary to enclose a considerable volume about the module, with access below the module and vents above it.

The following guidelines refer to the application of electronic modules and other components in a basically crude mechanical appliance.

1) Insertion and retraction of the module, and any *in situ* adjustment, should be easily accomplished so that minimal damage is caused by the unskilled assembler or repairer newly encountering an 'electronic box'.
2) The mounting should be firm but not rigid, allowing some play if pressure is applied while adjusting, fitting connectors, etc.
3) Mounting should be such that the ambient temperature and atmospheric conditions are moderate, rather than marginally within the module rating.
4) While the above recommendations might indicate an open and accessible mounting position, care should be taken to avoid possible accidental knocking during assembly and testing. The module should not be harmed by accidental bending or distortion of the access cover.

The recommendations given in this section are based on experience with modules intended for the electronic control of domestic appliances. They are by no means exhaustive, but some or all are certainly relevant to the application of electronic assemblies in an appliance which is not primarily regarded as a piece of electronic equipment, and whose design is not therefore primarily based on the requirements of the electronic components themselves.

Testing and servicing modules containing ICs

If adequate attention has been paid to the safe operation of integrated circuits, then the designer may be satisfied that no reliability problems will arise. Nevertheless, potential hazards can arise during equipment manufacture, particularly when alignment, testing, and servicing are carried out. Consider, for example, the formation of inrush currents.

The supply current to an IC during switch-on may have a transient component because of the various capacitances, some quite large, connected to the other pins of the IC. The capacitors must be charged to their operating potentials (Fig.13). In the complete equipment the rate of rise of the supply voltages at switch-on may be restricted, and the circuit designer will have established that the ICs operate safely. The designer of a factory test jig, however, may be unaware of such considerations and may have arranged, as is typically the case, for a permanently operating low-impedance power supply unit to be connected to the module under test by a simple on/off switch. Under these conditions the IC inrush currents can be much greater than those accommodated by the circuit design, and can be well outside the safe limits for the IC.

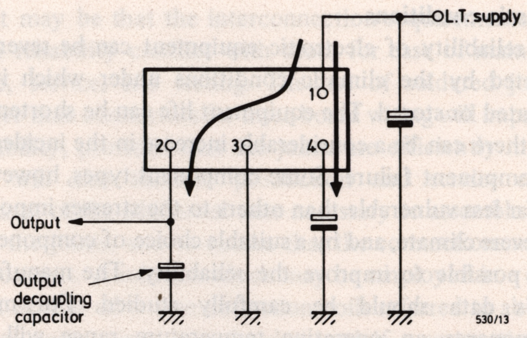

Fig.13 — Example of formation of inrush currents

A related problem arises when the ICs are mounted in sockets. If the operation of an IC is in doubt, it is commonly removed from its socket and replaced by another, without first switching off the power supply. Again, excessive inrush currents can occur: it is possible for a complete batch of new ICs to be destroyed, one after another, by an inadequately-briefed operator.

In some cases the supply voltages to a module containing ICs can, by handling errors, be made higher than the rated voltages of the IC. Fig.14 shows an example of a supply arrangement where the l.t. supply voltage is dropped to a value appropriate to pin 1 of the IC by a series resistor R_1 and a decoupling capacitor C_1. Another arrangement is that where a constant current is required at one terminal of an IC, and the current is derived from an external point which is at a much higher voltage than the IC could withstand. This configuration is illustrated at pin 2 of the (theoretical) IC in Fig.14. If either of these arrangements is used then the designer will have established that all circuit tolerances have been taken into account for normal operation of the equipment. However, in both cases a hazard can arise if the IC is removed from a socket and replaced without switching off the power supplies. A particularly severe hazard is represented by the charge potential, developed across C_2 while the IC socket is vacant and re-applied to the replacement IC, which will reach the full h.t. voltage.

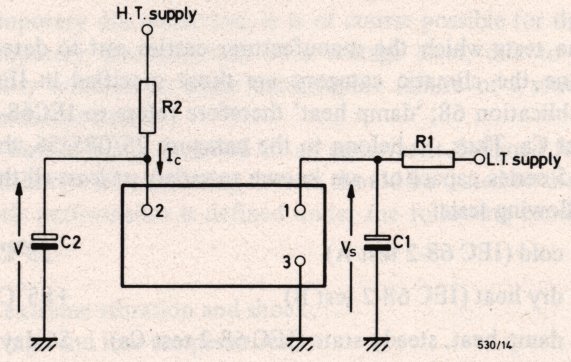

Fig.14 — Example of high-voltage hazards

The safeguards are, clearly, warning notices on the equipment and in the service manual; adequate education of servicing personnel; and direct soldering of the ICs to the panel.

EFFECTS OF CIRCUIT DESIGN ON RELIABILITY

If the reliability of each individual component has been considered and, where deemed advisable, improved by derating, and if it has been determined that the interaction of the components with the power supplies, mechanical arrangements, and ambient conditions which constitute their environment is satisfactory, then the designer should proceed to examine the circuit itself and assess its reliability. Strictly, the circuit design is another aspect of the environmental design considered above, because the circuit is the immediate electrical environment of each component, but it is convenient to deal with circuit reliability separately because of the wide variety of requirements that the circuit design must meet.

First, and probably foremost in the mind of the designer, the circuit must fulfil its function: it must oscillate, amplify, switch, or perform whatever operation it is intended to perform. This requirement is perhaps the easiest for the designer to satisfy, and this article does not presume to give instruction on the subject. We are concerned that the circuit should function reliably, and in the first instance this implies reliability of operation so that, for example, the generation of a pulse or a waveform in one part of the circuit does not cause a spurious pulse or waveform to be generated in another part.

Secondly, the design of the circuit has a bearing on the reliability of its components. Provided that no gross errors have been made, catastrophic failures are unlikely. Nevertheless it is essential that all components operate at all times within (or well below) their rated maximum operating conditions, and that this situation is not jeopardised by an unfavourable combination of parameter tolerances.

Furthermore the possibility of secondary failure should, as far as possible, be avoided. Secondary failure describes the situation where a failure (not necessarily catastrophic) in one component gives rise to a failure (which may well be catastrophic) in another component or group of components.

Maximum operating conditions

Published data provide information on the capability of components, and it is the task of the circuit designer to evaluate the conditions to which the components will be subjected in the equipment, and to ensure that the limits are not exceeded under any circumstances – that is, that the equipment operates at all times within the prescribed conditions of voltage, current, dissipation, SOAR, temperature, and drive, and that any suggested precautions are taken.

First it is necessary to establish the nominal operating conditions of a component, omitting (at this stage) consideration of tolerances. Let us take, as a deliberately complex example, a colour television receiver line output stage. Examining the data regarding deflection coil sensitivity, we see that a current is given to scan the tube edge-to-edge. An overscan of at least 6% should therefore be added. The shunt inductance of the line output transformer should be taken into account. The loading effects due to the convergence circuit, picture tube heater supply, l.t. supply, a_1 supply, and e.h.t. supply are added. If the picture centring facility is provided, then this may also contribute to the loading and shunting of the line output transformer.

The effect on the circuit of component and operational tolerances must now be examined. This may be a complex matter. For the example cited above, Table 15 shows the statistical sum of the effects of component tolerances on the line output transistor collector current i_c and voltage v_c, and on the scan. Table 16 shows the operational tolerances to be expected; these are added arithmetically. Some drift of component values with life is to be expected, and those which tend to increase i_c, v_c, and scan are tabulated and summed in Table 17. The effects of adjustments expected during manufacture and servicing are shown in Table 18. Finally, in Table 19 the results shown in Tables 15 to 18 are added arithmetically to produce the maximum variation in i_c and v_c to be allowed for the circuit design. It remains necessary to calculate the transistor drive which must be of suitable proportions and within specified tolerances, to check the SOAR for the output transistor, scan rectification diodes, driver transistor, etc., and to provide suitable heatsinks.

It is necessary to consider the ambient temperature at which the equipment will operate, and the expected rise in temperature when the equipment is installed in a cabinet. For television receivers the effects of picture tube flashover will also be considered at the design stage.

TABLE 15

Component Tolerances

Component	Unit	Tolerance (%)	Effects of the tolerance on: Δi_c(%)	Δv_c(%)	Δscan(%)
Deflection coil inductance, L_y	mH	3.0	2.7	1.7	2.4
Deflection coil sensitivity, $L_y i_y$		2.0	1.8	1.3	1.6
Picture tube sensitivity		1.5% scan	1.0	1.0	1.5
Effects of width control adjustment		–	1.0	1.0	–
L.O. transformer inductance (10 L_y)	mH	10	0.3	0.2	0.3
L.O. transformer deflection coils turns ratio		0.5	0.5	0.3	0.5
Accuracy of harmonic tuning		10	0.5	0.5	0.3
L.O.T. + deflection coils capacitance	pF	5.0	–	1.25	1.1
Tuning capacitor	pF	5.0	–	1	1.1
S-correction capacitor	pF	10	2.0	0.5	2.0
L.O. transistor turn-off		–	–	1.0	0.5
Flashover protection resistor	Ω	5.0	0.25	0.25	0.35
E-W correction		Required range	–	1.0	1.0
Passive convergence			1.0	0.5	2.0
H.T. voltage setting	V	1.0	3.0	3.0	2.7
L.T. supply load variations	A	20	1.0	1.0	0.9
H.T. line temperature drifts	V	2.7	2.7	2.7	2.5
H.T. line drift with life	V	3.0	3.0	3.0	2.7
R.M.S. sum			6.20	5.74	6.31

TABLE 16

Operational Tolerances

Component	Unit	Tolerance (%)	Effects of the tolerance on: Δi_c(%)	Δv_c(%)	Δscan(%)
Mains voltage variations	V	± 10	± 2.0	± 2	1.0
Beam current variations 0 to 1.5	mA		9*	5	1.5
Out of sync	kHz	−10	+ 10	+ 10	–
Line frequency variation due to VCR	kHz	± 2	± 2	± 2	
Arithmetic sum of +ve tolerances			14	14	2.5

*This tolerance is normally taken into account at the design stage of the line timebase and is therefore not added.

TABLE 17

Drift with Life

Component	Unit	Drift (%)	Effects of the drift on: Δi_c(%)	Δv_c(%)	Δscan(%)
Tuning capacitor	pF	−5	–	+ 1.25	−1.1
L.O. transformer	pF	−5	–	+ 1.25	−1.1
S-correction capacitor	pF	−5	−1.0	+ 0.2	+ 1.0
Flashover protection resistor	Ω	+ 5	−0.25	−0.25	−0.35
H.T. line drift*	V	± 3	± 3.0	± 3.0	± 2.7
Arithmetic sum of +ve tolerances			0.0	2.7	3.7

*Already taken into account in Table 15.

TABLE 18

Manufacturing and Servicing Adjustments

Adjustment	Unit	Total amount (%)	Amount already accounted for (%)	Net adjustment (%)	Effect of adjustment on: Δi_c(%)	Δv_c(%)
H.T. line	V	10	3 + 3	+4	+4	+4
Line frequency	kHz	12	10	+2	+2	+2
L.T. load	A	−50	20	−30	+1.5	+1.5
Arithmetic sum					7.5	7.5

TABLE 19

Addition of Tolerances for Maximum of I_C and V_C

Tolerance	Δi_c(%)	Δv_c(%)
Components	6.20	5.74
Operational (excluding VCR)	12.0	12.0
Drift with life	0.0	2.7
Manufacturing and servicing	7.5	7.5
Arithmetic sum	25.7	27.94

The line timebase, for example, will be protected and will also be designed to withstand the residual increase in peak collector voltage which may occur: indeed it is advisable to protect the whole television system.

Interaction between stages

A circuit may operate satisfactorily and reliably when alone, but may exhibit unexpected behaviour when assembled into a complete equipment. The disturbances observed often affect not only the performance of the equipment, but also component operating conditions and, therefore, life.

For example, different circuits in an equipment may operate from different power supplies. Where a power output stage is fed by a stabilised supply and its driver stage from an unstabilised supply or from raw a.c., it is important to ensure that the output stage is fully driven at the lowest expected mains voltage. Even where stabilised supplies are used for both driver and output, the switch-on and switch-off conditions must be investigated. The rate of rise of the supply voltage to the driver could be smaller than that to the output, or, conversely, at switch-off the drive could disappear while there is still appreciable supply voltage at the output stage. In either case the output transistor is starved of drive. With a large discrepancy there will be immediate failures; in less extreme cases the periodic stress on the transistor will cause short life or high failure rates.

TTL integrated circuits

The design of reliable systems using ICs necessitates the application of certain precautions and special techniques to the functional design itself, as well as the power supply, decoupling, etc. considerations dealt with elsewhere.

Unused gate inputs

Where more inputs to a TTL gate are available than will actually be used, the 'spare' inputs can be dealt with in a number of ways, not all of which give equal performance or reliability.

1) Leave them floating. This reduces the system speed, introducing a delay of about 1ns because the stray capacitance to ground must be charged via the input base resistance. Furthermore, floating inputs are prone to noise pick-up.
2) Connect them to +V_{cc}. Direct connection is inadvisable because the inputs may be damaged by supply rail transients.
3) Connect them to V_{cc}, with series resistance. This method is safe, but it increases the propagation delay by about 0.5ns.
4) Strap them to another input of the same gate. This method is the most appropriate if sufficient fan-out is available at the previous stage. The load of each unused input can be regarded as 1 in the '0' state and 1.5 in the '1' state.
5) Connect them to the output of an unused gate whose input is grounded. This method is the best if a spare gate is available. Furthermore, if the inputs of all unused gates are grounded then the system current drain is reduced.

The unused inputs of all OR and NOR gates and of the unused sections of AND-OR-INVERT gates must be grounded.

Flip-flops

For the best noise immunity, clock pulse rise- and fall-times should be less than 150ns. Preset and clear pulses should be present for longer than is the clock pulse, where used. Unused preset, clear, J, and K inputs should be treated in the same manner as are unused gate inputs.

Interfacing

For calculating input resistor values it is necessary to observe the following maximum rating for FJ (74N) series IC inputs.

Maximum d.c. current into input	+1 to −1.6mA
Maximum d.c. voltage at input	+5.5 to −1.5V
Maximum d.c. voltage difference between two inputs of the same gate	5.5V

The latter restriction is important if two or more inputs of a gate are used separately, as in Fig.15. To keep within the device ratings the minimum value of resistor R is given by:

$$R = (V_{cc}\,\mathrm{max} - V_{low} - 5.5)\ \mathrm{k}\Omega.$$

In normal systems where V_{cc} may be as high as +7V and V_{low} is 0V, the minimum value of pull-up resistance is 1.5kΩ.

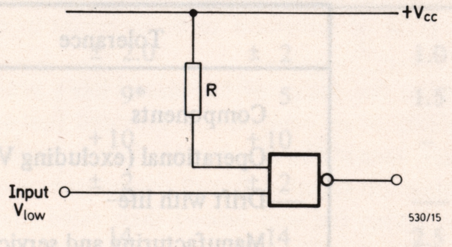

Fig.15 – Two TTL inputs used separately

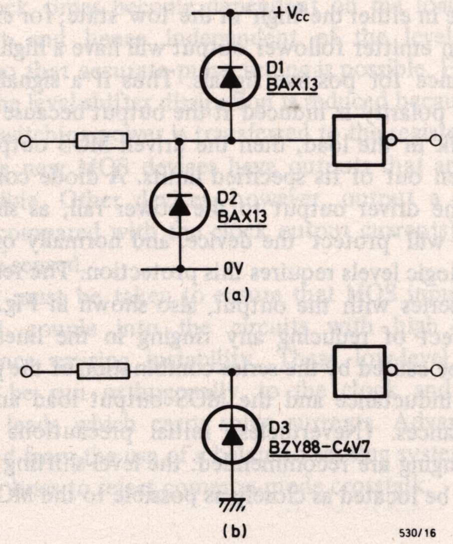

Fig.16 – Resistive source:
(a) with clipping diodes;
(b) with voltage reference diode

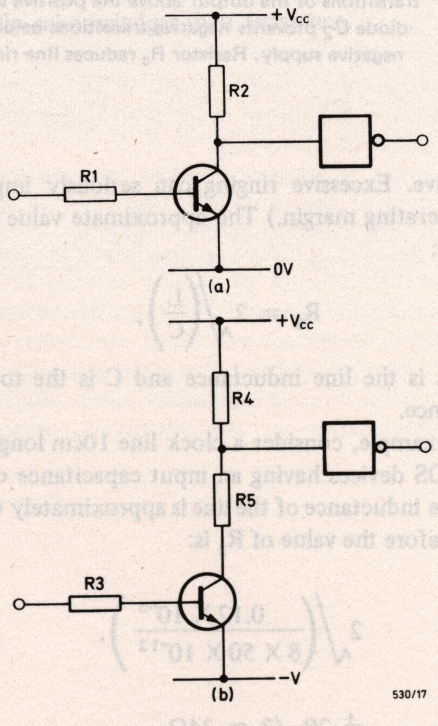

Fig.17 – TTL drive circuit:
(a) positive inputs;
(b) positive or negative inputs

Driving

The simplest drive source is resistive with a pair of clipping diodes (Fig.16a) or a voltage reference diode (Fig. 16b). If the driving source voltage levels are unsuited to either of these methods then a transistor driver circuit can be used. Two such circuits are shown in Figs.17a and 17b. In Fig.17a the input signals are always positive with respect to ground, and the value of R_2 is found from the equation above. In Fig.17b, the input signals can be either positive or negative. Resistor R_4 must be able to provide the 'high' input state drive current: a value of 4.7kΩ is appropriate. Resistor R_5 must be capable of sinking 1.6mA for each separate gate that it drives.

Inputs driven from switches

Where a gate is driven by a mechanical contact, the arrangement of Fig.18 may be used. Resistor R reduces the possibility of noise pick-up when the switch is open. However, contact bounce in mechanical switches causes the generation of a train of spurious pulses at each operation. It is better to use the switch to trigger a monostable which can provide a single pulse if required, or delay the application of the signal until switch bounce has ended. Alternatively, if a changeover switch is available then a pair of cross-coupled gates may be used, as in Fig.19.

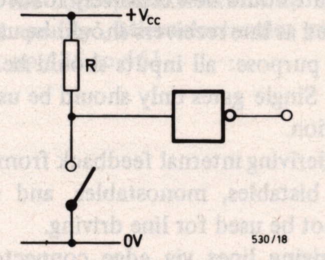

Fig.18 – TTL gate driven by mechanical contact

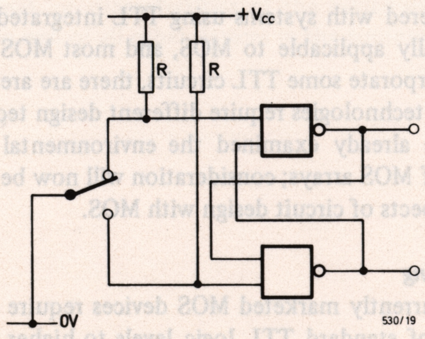

Fig.19 – TTL gate driven by mechanical contact via cross-coupled gates

Line driving
If the length of an interconnection between TTL circuits exceeds 50cm, then the interconnection must be regarded as a transmission line. The following guidelines have been established to eliminate the difficulties associated with line driving between TTL gates.

1) Direct wire interconnections with no specific ground return are suitable only where the length is less than 25cm. A ground plane is always desirable.
2) Direct wire interconnections exceeding 25cm in length must be routed close to a ground plane.
3) Line driver and line receiver gates must be decoupled, at the package, by a 0.1μF capacitor.
4) When coaxial or twisted-pair cables are used, a suitable design characteristic impedance is 100Ω. Lower impedances present drive difficulties, and higher impedances introduce crosstalk.
5) Transmission-line ground returns must be carried through at both the transmitting and receiving ends.
6) At the transmitting end, reverse-terminate the line with 27 to 47Ω in series with the line to reduce reflected negative overshoot.
7) Gates used as line drivers should perform that function only. If further gates, as well as the line, are driven then they could receive erroneous inputs because of line reflections. Furthermore, unwanted delays could be introduced into the system, and the driving gate could be excessively loaded.
8) Gates used as line receivers should be used exclusively for that purpose: all inputs should be connected to the line. Single gates only should be used at the line termination.
9) Devices deriving internal feedback from their outputs, such as bistables, monostables, and shift registers, should not be used for line driving.
10) Gates driving lines via edge connectors should be mounted near the connector ground pin, to provide a low-impedance earth return for line currents.

MOS integrated circuits
Although many of the design problems and solutions encountered with systems using TTL integrated circuits are equally applicable to MOS, and most MOS systems will incorporate some TTL circuits, there are areas where the two technologies require different design techniques. We have already examined the environmental requirements of MOS arrays; consideration will now be given to some aspects of circuit design with MOS.

Interfacing
Many currently marketed MOS devices require the conversion of standard TTL logic levels to higher voltages. Level-shifting circuits must have a low output impedance during the edge transition, to drive the capacitative MOS inputs. A high-impedance output in one direction is possible in either the 'high' or the 'low' state; for example, an n-p-n emitter follower output will have a high output impedance for positive signals. Thus if a signal of the correct polarity is induced at the output because of, say, crosstalk in the load, then the driven MOS output may be taken out of its specified limits. A diode connected from the driver output to the power rail, as shown in Fig.20, will 'protect' the device, and normally only one of the logic levels requires this protection. The resistance R_s in series with the output, also shown in Fig.20, has the effect of reducing any ringing in the lines which might be caused by the series combination of the printed-wiring inductance and the MOS output load and stray capacitances. (Nevertheless initial precautions against such ringing are recommended: the level-shifting circuits should be located as closely as possible to the MOS array they drive. Excessive ringing can seriously impair the MOS operating margin.) The approximate value of R_s is given by:

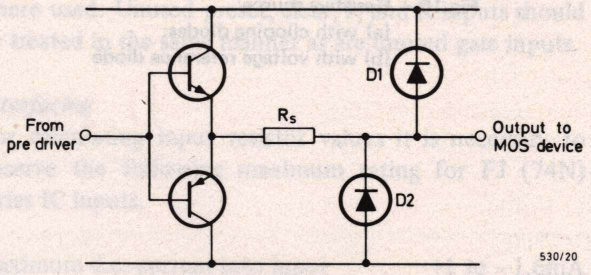

Fig.20 – MOS level-shifting circuit. Diode D_1 prevents positive transitions of the output above the positive supply; diode D_2 prevents negative transitions below the negative supply. Resistor R_s reduces line ringing

$$R_s = 2\sqrt{\left(\frac{L}{C}\right)},$$

where L is the line inductance and C is the total load capacitance.

For example, consider a clock line 10cm long driving eight MOS devices having an input capacitance of 50pF each. The inductance of the line is approximately 0.12μH, and therefore the value of R_s is:

$$2\sqrt{\left(\frac{0.12 \times 10^{-6}}{8 \times 50 \times 10^{-12}}\right)},$$

$$\doteq 20\sqrt{3} \approx 34\Omega.$$

The inclusion of resistor R_s will improve the signal quality, but at the expense of an increase in edge speed. The clock times become dependent on the load time-constant and hence independent of the level-shifter speed, so that accurate pulse timing is possible. Furthermore, the level-shifter dissipation is reduced because part of the switching power is transferred to the register.

Some new MOS devices have outputs that are TTL-compatible. Other devices, however, output a current (small compared with the clock output currents) which must be sensed.

Care must be taken to ensure that MOS input levels do not couple into the circuits with high output impedance causing instability. These low-level signals should be run orthogonally to the clock and power supply leads which carry spike currents. Advantage is obtained from the use of a balanced sensing system, with dummy lines to reject common-mode crosstalk.

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REFERENCES

1. GATES, T.W. and BALLARD, M.F., 'Safe Operating Area for Power Transistors', **Mullard Technical Communications**, Vol.13, No.122, April 1974, pp.42 to 65.
2. U.S. Department of Defense, 'Reliability stress and failure rate data for electronic equipment', Military Standardization Handbook MIL-HDBK-217, and subsequent editions.
3. '350mW small-signal plastic transistors for professional equipment', Technical Note 28, TP1502, Mullard Limited, 1975.
4. '1W plastic transistors for professional equipment', Technical Note 29, TP1503, Mullard Limited, 1975.
5. STANLEY, K.W., 'Reliability and stability of carbon film resistors', **Mullard Technical Communications**, Vol.11, No.110, March 1971, pp.223 to 234.
6. 'High-grade long-life aluminium electrolytic capacitors', New Product Information, TP1452, Mullard Limited, 1974.
7. DUMMER, G.W.A., 'Failure rates of electronic components', charts published in **Electronic Components**, September 1967 (republished 1970); and numerous other publications.
8. Rome Air Development Center, 'Reliability Notebook', RADC-TR-67-108.
9. IEC Publication 271 (Reliability of electronic components: preliminary list of basic terms and definitions).
10. BREWER, R., 'Reliability terms and definitions based on the conceptual relationship between reliability and quality', **Microelectronics and Reliability** 11, 1972, pp.435 to 461.

APPENDIX 1

Reliability Definitions

Reliability is the ability of an item to perform a required function under stated conditions for a stated period of time (Ref.9). 'Time' in this definition may be replaced by distance, cycles, etc. as appropriate, and 'item' is used to denote any electronic part, sub-system, system, or equipment that can be individually considered and separately tested. To avoid repetition, 'item' includes items, population of items, sample, etc. where the context justifies its use.

An alternative, quantitative definition of reliability is given in Ref.9; that is: reliability is the characteristic of an item expressed by the probability that it will perform a required function under stated conditions for a stated period of time. This probability (normally expressed as a percentage) may also be called *success ratio. Failure,* the termination of the ability of an item to perform its required function, may be sudden, gradual, complete, partial, catastrophic (sudden and complete), or degradation (gradual and partial), and the limits of partial failure must be defined. Other commonly-used quantitative expressions of reliability on an attributes basis (Ref.10) are:

mean time between failures (MTBF),

mean time to failure (MTTF),

mean life, and

percentile life.

These quantitative expressions of reliability may be used in various circumstances. They may refer to data resulting from tests carried out under controlled conditions for a restricted period of time. The results of such tests give an *observed* reliability characteristic: for example, observed failure rate.

Frequently in reports or statements this observed figure is not quoted, but instead some statistical treatment is used and the results are quoted as the upper or lower limit of the *confidence interval* at a stated probability level. This is called the *assessed* value of a reliability characteristic: for example, assessed failure rate. This is the confidence interval relating to the observed figure, but still limited to the length of time of the original data.

The *extrapolated* characteristic, as its name implies, is an extension, for longer times or different test conditions, from the observed data.

In the case of equipment, where we take the design consideration of the equipment into account as well as the failure characteristics of the components, we have a variation which is called the *predicted* failure rate.

APPENDIX 2

Rating Systems

Absolute maximum rating system

Absolute maximum ratings are limiting values of operating and environmental conditions applicable to any device of a specified type as defined by the published data, and should not be exceeded under the worst probable conditions.

These values are chosen by the device manufacturer to provide acceptable serviceability of the device, taking no responsibility for variations in equipment or environment, nor for the effects of changes in operating conditions due to variations in the characteristics of the device under consideration and of all other devices in the equipment.

The equipment manufacturer should design so that initially and throughout life no absolute maximum value for the intended service is exceeded with any device under the worst probable operating conditions with respect to variations in supply voltage, environment, equipment components, equipment control adjustment, load, signal, or characteristics of the device under consideration and of all other devices in the equipment.

Design-centre rating system

Design-centre ratings are limiting values of operating and environmental conditions applicable to a bogey device of a specified type as defined by its published data, and should not be exceeded under normal conditions.

These values are chosen by the device manufacturer to provide acceptable serviceability of the device in average applications, taking into account normal changes in operating conditions due to variations in supply voltage, environment, equipment components, equipment control adjustment, load, signal, or characteristics of all other devices in the equipment.

The equipment manufacturer should design so that initially no design-centre value for the intended service is exceeded with a bogey device in equipment operating at the stated normal supply voltage. The device manufacturer takes account of normal random variations in conditions and components. This system is mainly applicable where circuit design is based upon considerable past experience.

Design-maximum rating system

Design-maximum ratings are limiting values of operating and environmental conditions applicable to a bogey device of a specified type as defined by its published data, and should not be exceeded under the worst probable conditions.

These values are chosen by the device manufacturer to provide acceptable serviceability of the device, taking into account the effects of changes in operating conditions due to variations in the characteristics of the device under consideration.

The equipment manufacturer should design so that initially and throughout life no design-maximum value for the intended service is exceeded with a bogey device under the worst probable operating conditions with respect to variations in supply voltage, environment, equipment components, equipment control adjustment, load, signal, or characteristics of the device under consideration and of all other devices in the equipment.

APPENDIX 3

Confidence Level

The simplest way to obtain a reliability figure from observed data is to calculate the observed failure rate; that is, the ratio of the number of failures found in a test to the number of component-hours tested. For example, if 1000 components were tested for 1000 hours and one failure was found, then the observed failure rate of this component under the conditions of the test is 1×10^{-6}/h, sometimes written as 0.1% per 1000h.

In practice the observed reliability figure is based on only a small part of the entire production, and so an incidentally favourable or unfavourable random sampling may cause the observed reliability figure to differ from the actual figure. To reduce the risk of quoting too favourable a reliability figure, an assessed failure rate may be quoted which is higher than the observed figure. It is then stated that the failure rate is given with a certain *confidence level*, say 60%, where the percentage indicates the probability that the actual failure rate is less than the quoted assessed failure rate.

To extend the previous example, where the observed failure rate after testing 1000 components for 1000 hours was 1×10^{-6}/h: it can be stated with a confidence level of 60% that the actual failure rate is less than 2×10^{-6}/h, and with a confidence level of 95% that it is less than 4.7×10^{-6}/h.

A confidence limit is established by artificially increasing the number of failures observed. The increase depends on the chosen confidence level, the number of failures observed, the size of the total population tested, and the distribution of the failures. Table 20 gives examples of observed failure rates and assessed failure rates with 60% and 95% confidence levels, based on the number of failures found after tests of 2.5×10^6 component hours. The assessed failure rates are based on the Poisson distribution.

If the previous example of an observed failure rate of 1×10^{-6}/h is interpolated into Table 20, then there is an apparent discrepancy: the assessed failure rates given in the example are greater than those which would be given by the table. The reason for this is that Table 20 is based on a greater number of component-hours tested than is the example. This illustrates that if more test information is available, then the observed failure rate is more plausible and is more closely approached by the assessed failure rate.

TABLE 20

Observed and Assessed Failure Rates Calculated from 0, 1, 2, 3, 5, and 10 Observed Failures in Tests of 2.5×10^6 Component hours

Number of failures observed	Observed failure rate ($\times 10^{-6}$/h)	60% confidence level: artificially increased number of failures	60% confidence level: assessed failure rate ($\times 10^{-6}$/h)	95% confidence level: artificially increased number of failures	95% confidence level: assessed failure rate ($\times 10^{-6}$/h)
0	0	0.9	0.4	3.0	1.2
1	0.4	2.0	0.8	4.7	1.9
2	0.8	3.1	1.2	6.3	2.5
3	1.2	4.2	1.7	7.8	3.1
5	2.0	6.3	2.5	10.5	4.2
10	4.0	11.5	4.6	17.0	6.8

APPENDIX 4

Unit Reliability Breakdown for Domestic Motor Speed-control Module

Table 21 shows how the reliability of a complete electronic module is apportioned among its components, and how a value for the mean time between failures (MTBF) of the module is calculated.

The calculation of component stress is for a limit component operating under worst-case electrical and temperature conditions. Under these conditions no component is stressed by more than 80% of its maximum rating. For typical components under normal operating conditions, the maximum stress would be substantially lower than 80% of the rating.

For most of the components of the module, the worst-case stress level is less than 80% of the rating. The 'stress' column in Table 21 shows the actual worst-case stress as a proportion of the maximum rating.

The base failure rates given are obtained from appropriate sources, and two correction factors are applied. The temperature correction factor C_1 is a function of the ambient temperature at which the equipment is designed to operate (for the module being considered, C_1 is unity). The rating correction factor C_2 is obtained from Mullard tables based on field reliability information; it is a figure appropriate to the selected stress level for a particular component.

For each component, the corrected failure rate is the product of base failure rate, stress, C_1, and C_2. This product is then multiplied by the quantity of the component used in the module, to give the total failure rate due to each component type. The overall module failure rate is then the sum of these figures, and the mean time between failures is the reciprocal of the sum.

The calculated MTBF is very high in this case. The object of a reliability apportionment exercise such as this is not only to ensure that the MTBF is somewhat longer than the minimum required, but also to ensure that the stress level of every component is sufficiently low.

TABLE 21

MTBF Calculation for Motor Speed-control Module

Component type	Base failure rate ($\times 10^{-9}$/h)	Stress (proportion of maximum rating)	Temperature correction factor C_1	Rating correction factor C_2	Corrected failure rate ($\times 10^{-9}$/h)	Quantity used in module	Total failure rate ($\times 10^{-9}$/h)
Resistor	10	0.1	1	6.0	6	20	120
Resistor	4	0.5	1	1.4	2.8	2	6
Resistor	4	0.8	1	1.3	4.2	1	4
Preset variable resistor	10	0.1	1	6.0	6	1	6
N.T.C. thermistor	10	0.1	1	6.0	6	1	6
Protection resistor	10	0.1	1	10.0	10	1	10
Capacitor	10	0.2	1	5.0	10	2	20
Capacitor	10	0.4	1	3.3	13.2	1	13
Electrolytic capacitor	75	0.8	1	1.3	78	4	312
Diode	20	0.2	1	2.0	8	2	16
Diode	30	0.8	1	2.1	50	1	50
Diode	20	0.2	1	2.0	8	1	8
Zener diode	60	0.2	1	2.0	24	2	48
Trigger device	125	0.3	1	1.3	49	1	49
Transistor	100	0.4	1	1.5	60	1	60
Thyristor	250	0.8	1	1.9	375	1	375
Solder joint (hand)	2	–	1	1.0	2	6	12
Solder joint (machine)	0.2	–	1	1.0	0.2	97	19
TOTAL							1134

Total module failure rate = 1134 × 10^{-9}/h

$$\text{MTBF} = \frac{1}{1134 \times 10^{-9}} = 0.88 \times 10^{6}\,\text{h}$$